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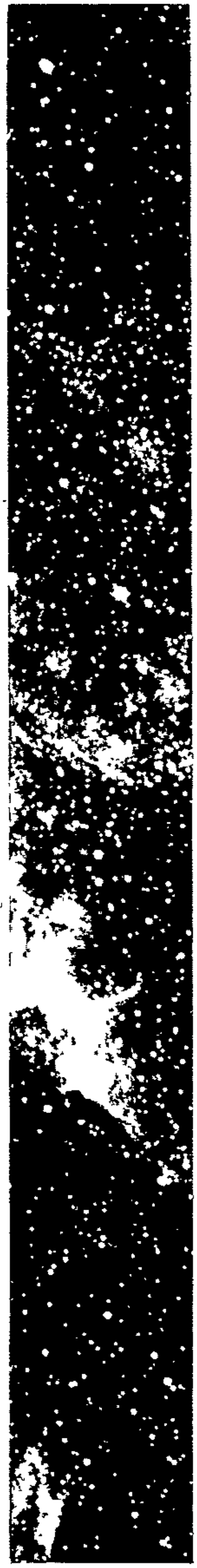

TELEVISION BROADCAST SATELLITE (TVBS) STUDY RESEARCH AND TECHNOLOGY IMPLICATIONS REPORT

VOLUME II

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

CONTRACT NAS 3-9708

GENERAL ELECTRIC COMPANY
SPACE SYSTEMS ORGANIZATION
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OCTOBER 6, 1969

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PREFACE

The Television Broadcast Satellite (TVBS) study was performed, under NASA Contract NAS 3-9708, from August 1967 through January 1969 by the General Electric Company. The study results are presented in the following three volumes:

- Volume I - TVBS Summary Report
- Volume II - TVBS Research and Technology Implications Report
- Volume III - TVBS Technical Report

ABSTRACT

This report presents the research and technology implications associated with the Television Broadcast Satellite (TVBS) Study. Technologies were investigated which were required by the satellite system conceptual designs generated in the TVBS study. Pertinent technologies were identified, their parameter improvements with time were predicted and their impact on significant TVBS system parameters was evaluated. Ranking criteria were used to list technologies in order of recommended priority for development as a function of satellite power level and launch date. The most critical items are high efficiency transmitters, high power/voltage components, large solar arrays, interaction of flexible structures with control systems, thermal control of high power transmitters, highly reliable long life operation, and low cost ground receiving systems. The study demonstrates that broadcast satellites are feasible in the next decade.

SUMMARY

This Research and Technology Implications (R&TI) report is based upon the comprehensive Television Broadcast Satellite (TVBS) study performed under NASA contract NAS 3-9708. The TVBS study was a satellite systems design study which investigated technical and economic factors associated with television broadcasting from space. The TVBS study reached three important conclusions: (1) high power broadcast satellites are feasible in the next decade if current technology and subsystem development is continued; (2) satellite systems are cost-effective for large coverage areas; (3) turnkey operation can be achieved sooner by satellite than by ground-based systems if the objective is a new service to essentially the entire population of a region.

This R&TI report presents the technology evaluation supporting the conclusion that broadcast satellites are feasible within the next decade. Technologies were investigated in order to determine those additional programs required to develop or advance the state of the art. Pertinent technologies were identified, their parameter improvements with time predicted, and their impact on significant system parameters evaluated. Ranking criteria were established to permit listing the finally selected technologies in order of recommended priority for development funding as a function of varying satellite power level and launch date classifications. The most critical items (for high power broadcast satellite applications) are high efficiency transmitters, components for handling of high voltage and high power, interaction of flexible structures with control systems, deployment of large arrays of solar cells, low-cost ground receiving systems, thermal control of high-power transmitter components, and highly reliable long life (2 to 5-year) operation.

Candidate technologies were selected primarily on the expected effect which that development effort might have upon either the system cost, weight, life and performance, or subsystem feasibility. The state-of-the-art was assessed for each technology as a further indication of its critical nature and the need for additional development effort. The state-of-the-art study included not only a survey of the general capability and development status existing today and the predicted capability as of 1971 or beyond, but also an identification of the major problems, currently funded efforts (where known), and additional effort needed but not presently funded.

Criteria were formulated (using the above factors) for ranking the technologies according to the degree of system impact each improvement would have, and according to the technology development risk and required lead time. The final priority listing of technologies is shown in Table A as a function of satellite power and launch date. Differences in priority among the items in any one category are considered to be relatively small, whereas major priority differences exist between the first, second and third priority groups for each generation satellite.

If satellite system weight and cost were not obstacles, then all required system functions could be performed by 1971 state-of-the-art subsystems. However, the technologies shown in Table A need continued development so that subsystem designs may be optimized for minimum cost and weight consistent with required performance. It is concluded that Broadcast Satellites are feasible in the next decade if current technology and subsystem development is continued.

Table A. TVBS Subsystem Technology Priority List

PRIORITY CATEGORY	SATELLITE CLASS		
	LOW SOLAR ARRAY POWER (1–3 KW; EARLY 1970'S	MEDIUM SOLAR ARRAY POWER (3–10 KW, MID-1970'S)	HIGH SOLAR ARRAY POWER (10–30 KW; LATE 1970'S)
FIRST	HIGH EFFICIENCY MICROWAVE TUBE GROUND RECEIVING SYSTEMS HIGH VOLTAGE POWER CONDITIONING HIGH EFFICIENCY GRIDDED TUBE UHF TRANSMITTER CIRCUITS	HIGH EFFICIENCY MICROWAVE TUBE GROUND RECEIVING SYSTEMS HIGH VOLTAGE POWER CONDITIONING ATTITUDE CONTROL OF FLEXIBLE STRUCTURES SOLAR ARRAY DEPLOYMENT HIGH EFFICIENCY GRIDDED TUBE UHF TRANSMITTER CIRCUITS	ATTITUDE CONTROL OF FLEXIBLE STRUCTURES HIGH EFFICIENCY MICROWAVE TUBE GROUND RECEIVING SYSTEMS HIGH VOLTAGE POWER CONDITIONING SOLAR ARRAY DEPLOYMENT HIGH EFFICIENCY GRIDDED TUBE UHF TRANSMITTER CIRCUITS HIGH VOLTAGE HANDLING HIGH VOLTAGE SOLAR ARRAY THERMAL–TRANSMITTER INTERFACE
SECOND	SOLAR ARRAY DEPLOYMENT HIGH VOLTAGE HANDLING THERMAL–TRANSMITTER INTERFACE HEAT PIPES DC ROTARY JOINT RF ROTARY JOINT	HIGH VOLTAGE HANDLING THERMAL–TRANSMITTER INTERFACE HEAT PIPES DC ROTARY JOINT RF ROTARY JOINT HIGH VOLTAGE SOLAR ARRAY HIGH POWER RF COMPONENTS 2–AXIS SOLAR ARRAY DRIVE	HEAT PIPES DC ROTARY JOINT RF ROTARY JOINT HIGH POWER RF COMPONENTS 2–AXIS SOLAR ARRAY DRIVE SOLAR CELL AND ARRAY MANUFACTURE REFLECTOR ANTENNA POWER HANDLING REFLECTOR ANTENNA BEAM POINTING REFLECTOR ANTENNA MULTI–BEAMS MICROWAVE TRANSMITTER CIRCUITS
THIRD	HIGH VOLTAGE SOLAR ARRAY HIGH POWER RF COMPONENTS REFLECTOR ANTENNA POWER HANDLING REFLECTOR ANTENNA BEAM POINTING REFLECTOR ANTENNA MULTI–BEAMS MICROWAVE TRANSMITTER CIRCUITS	REFLECTOR ANTENNA POWER HANDLING REFLECTOR ANTENNA BEAM POINTING REFLECTOR ANTENNA MULTI–BEAMS MICROWAVE TRANSMITTER CIRCUITS MECHANICALLY STEERABLE ANTENNA ARRAY	MECHANICALLY STEERABLE ANTENNA ARRAY ELECTRONICALLY STEERABLE ANTENNA ARRAY

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SECTION 1

INTRODUCTION

This Research and Technology Implications Report (R&TI) presents results obtained during the Television Broadcast Satellite (TVBS) study. The TVBS study phases are shown in Figure 1-1 with the technology tasks enclosed in a heavy border. The results of the TVBS study are given in Volumes I and III (TVBS Summary Report and TVBS Technical Report).

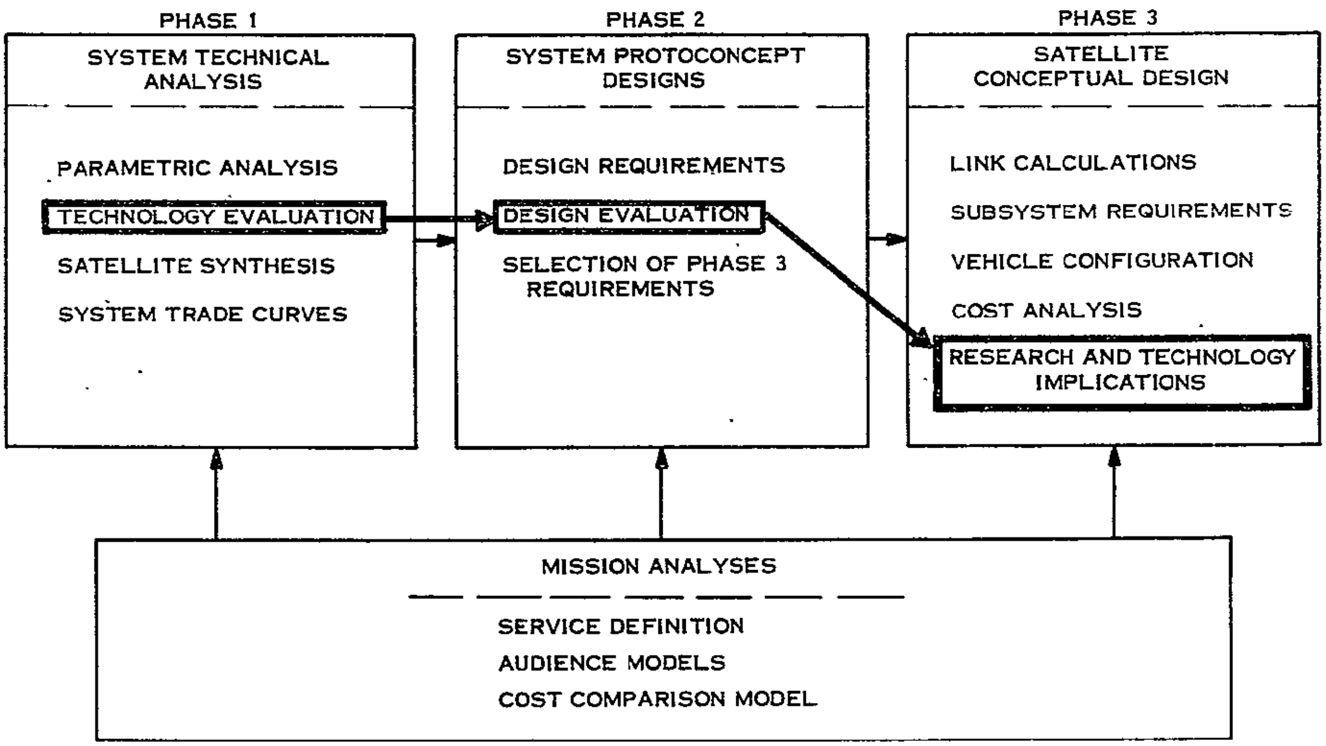

Figure 1-1. TVBS Program Plan

The TVBS study objectives shown in Figure 1-1 were: (1) define and examine in detail technological and cost factors affecting feasibility of a Broadcast Satellite in the 1970-75 time period through the synthesis of feasible satellite system configurations, (2) develop parametric data for spacecraft subsystems, and (3) develop conceptual system designs. The objectives and scope of the study required development of a large number of satellite and ground system configurations. In order to accomplish the study, a three phase program was defined: (1) a System Technical Analysis phase, (2) a System Protoconcept Design phase, and (3) a Satellite Conceptual Design phase. The supporting mission analysis and system synthesis task consisted of mission definition to arrive at potential TV services of value, an audience analysis to define the range of audiences to consider for each type of service, and a cost comparison model to enable comparison of satellite broadcasting with alternative

terrestrial methods. During Phase 1, state-of-the-art and performance characteristics available in the early 1970's were estimated for satellite and ground system components and subsystems. This data permitted feasibility evaluation of synthesized systems and provided a basis for establishing research and technology implications and development program recommendations during Phases 2 and 3.

The technology evaluation was concerned with the evaluation of technologies underlying the TV Broadcast Satellite system requirements. This was done to determine those programs required to develop or advance the state of the art. Pertinent technologies were identified, their parameter improvements with time predicted, and their impact on significant system parameters evaluated. Ranking criteria were established to permit listing the finally selected technologies in order of recommended priority for allocating development funding.

A logical basis for selection of any particular technology is the magnitude of its impact upon one or more significant system parameters such as weight, size, cost, life, or performance. Candidate technologies were ranked to provide a basis for selecting the sequence in which additional development funds should be applied. Not only was the impact of the specific technology upon the TVBS system considered, but also the estimated cost, time, and risk associated with each technology development program. Also considered were the lead times needed for developing each required technology as compared to others.

SECTION 2

STATE OF THE ART

The following paragraphs present the state of the art for various broadcast satellite subsystems and components including the solar array, power conditioner, dc and RF rotary joints, transmitter circuits and output tubes, high power RF components, antennas, flexible structures effects, thermal control, attitude control, and ground receiver installations. In each case, the discussion covers the general capability available today throughout the aerospace industry and the major problems which still need solving. Also identified are currently funded efforts as well as those efforts required but not adequately funded.

2.1 SOLAR ARRAY PRIME POWER

2.1.1 GENERAL CAPABILITY

The solar array generates primary power for all the satellite subsystems by converting sunlight into electrical energy. The performance of a large area solar array is an important factor in the design of broadcast satellites for several reasons. First, the array is the major portion of the satellite cost and weight for medium and high power broadcast satellites. Secondly, since the solar array may consist of a large flexible structure requiring solar orientation, its possible interaction with the attitude control system becomes a significant consideration. Lastly, the array cannot be tested in its operating configuration in a reasonable ground simulation of the zero "G" environment.

Deployment of large structures and long life operation of solar tracking mechanisms on past space programs attest to the feasibility and potential performance of large solar arrays. The successful deployment of the large area (1344 square feet) micrometeoroid detection panels on Pegasus and the operation of the 356 square feet of solar array on one Agena military satellite configuration provide a basis of flight-proven experience for the feasibility of large area solar arrays. The approximately 9 watts per pound (and per square foot) capability exhibited by the Mariner 4 solar panels and the successful operation of the Nimbus solar array tracking mechanism for over two years provide proven performance baselines for power density and long life operation. Recent large-area design for flight applications includes the 1.5 watt SERT II panels which weigh nearly 2.5 pounds per square foot (4 watts per pound for a nominal output of 10 watts per square foot).

For the past several years it has been recognized that solar arrays would have to be used to provide the large power requirements until at least the mid-1970's because nuclear systems will probably not be available, cost-effective, or weight-effective in the sizes required until then. Thus, there are in progress several solar array development activities that will provide technology of benefit to broadcast satellites.

The anticipated state of the art in solar arrays may be described in terms of expected power capability and power per pound. Examples of advanced concepts are as follows. A Boeing/JPL development program includes the construction of a 12.5 kW foldout array subsystem (part of a 50 kW array design) which is designed to produce 20 watts/lb. General Electric is performing for JPL a design for a 2.5 kW roll-up array subsystem (part of a 10 kW array) which would provide 30 watts/lb. (A photograph of a full-scale demonstration model of this array is shown in Figure 2-1). On the basis of these programs, a 10 to 15 kW array with a specific performance of at least 30 watts/lb (or 33 lbs/kW) appears reasonable for a vehicle design start in 1971.

Table 2-1 indicates the present and anticipated state-of-the-art capability of solar arrays by listing parameters for several flight hardware and development programs.

2.1.2. MAJOR PROBLEMS

Critical technology problems are discussed in the following paragraphs. It should be noted that the problems associated with large solar arrays involve improved performance rather than a fundamental breakthrough into a new technology area. With unlimited weight and the lack of other system constraints, very large areas of solar arrays could be deployed in space.

The cost of the solar array fabrication is a large, identifiable, discrete item in a broadcast satellite program. Estimates during the TVBS study ranged from $400 to $500 per watt. Significant cost elements include the solar cell and cover glass costs, and the labor associated with assembling the very large number of piece parts in a solar array.

The solar array can be a large contributor to the over-all weight of a high power broadcast satellite system. Increasing the performance from 4 watts per pound (typical for the SERT II array) to 30 watts per pound (a goal for one of the current array development programs) reduces the weight of the array by 217 pounds for each kilowatt of electrical power. Most of the improvement is achieved by reducing the weight of the array structural elements rather than by increasing the solar cell performance.

Orientation of the array may be a problem because the equipment to orient the solar array is electromechanical. This type of hardware has historically presented a long life reliability design challenge.

The interaction between the attitude control system and the array when it is re-oriented may be a problem. A large solar array is inherently a large appendage on the vehicle and is likely to contribute a major portion of the moments of inertia. In order to be lightweight, the array will be unavoidably flexible so that its dynamic characteristics will interact with the orientation system.

The use of a high voltage solar array may be desirable if it reduces the requirements for the power conditioner. However, testing a high voltage array is a major problem because of personnel hazards. Electrical breakdown in orbit is another problem when dealing with

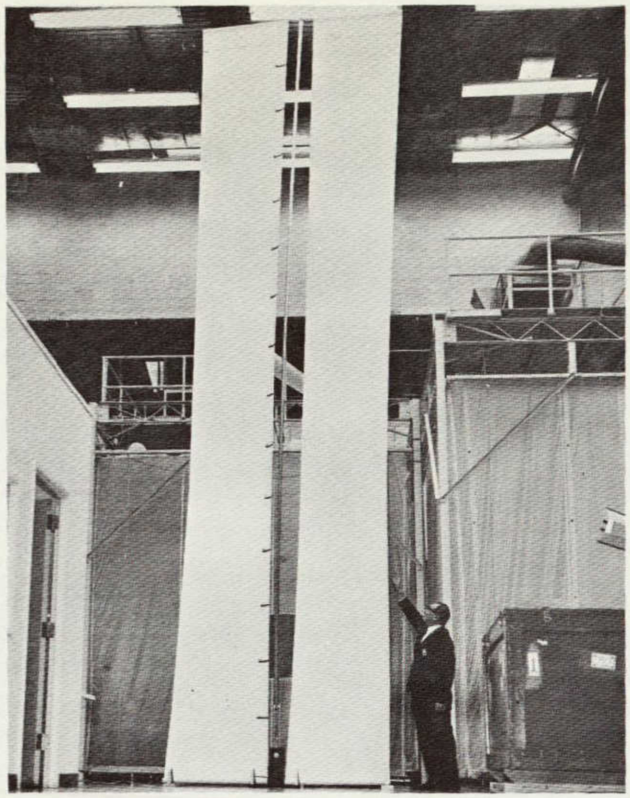

Figure 2-1. Demonstration Model of 30-Foot Boom Deployment Using Simulated Roll-up Solar Array

Table 2-1. Solar Array Design Parameter Values

Major Parameters	Nimbus 2	Mariner 4	SERT 2	Apollo Telescope Mount	Boeing Foldout Solar Array	GE Rollup Array	Hughes FISCA(1)	EOS Lightweight Rigid Solar Panel
Status as of September 1969	Has been flown	Has been flown	Flight Hdwr Delivered	Flight Hdwr Delivered	R&D Phase Completed	In R&D phase	R&D Completed	In Advanced Development
Total Array Area (ft^2)	50	70	188	1,509	4,924	1,000	93	1,239
Total Array Weight (lbs)	74	75	416	3,720	2,101	306	21	285
No. of Cells (2 cm x 2 cm, or equivalent)	10,944	14,112	33,300	246,264	1,026,368	220,704	21,080	241,920
Initial Power (watts, based on 45.7 mW/cell)	500	645	1,520	11,250	46,900	10,090	965	10,400(2)
Power Developed per Unit Weight (watts/lb)	6.8	8.6	3.7	3.0	22.3	30	22	27
Power Developed per Unit Area (watts/sq ft)	10	9.2	8.1	7.4	9.5	10.1	10.4	8.4
Weight per Unit Power (lbs/kW)	148	116	270	333	45	33	46.5	36.5

Notes: (1) Flight demonstration program now called LRSCA (Large Retractable Solar Cell Array)
(2) Based on 44.2 mV/cell for 4 mil thick cell
FISCA = Flexible, Integrated Solar Cell Array
SERT = Space Electric Rocket Test
EOS = Electro-Optical Systems, Inc.

high voltage levels. Possible failure of an entire high-voltage series string of solar cells due to an open or short circuit in (or between) one or more cells may conceivably be alleviated by using bypass diodes. This would permit a 30-volt potential to cause a cell to act as a diode. The problem could also be alleviated by employing appropriate series-parallel arrangements designed for high voltages. The deleterious effects of leakage currents caused by the electrical interaction of a high-voltage solar array with any plasma, charged particles, or outgassing products existing in the space environment, have yet to be investigated.

2.1.3 CURRENTLY FUNDED EFFORTS

Since the solar array is an item common to most long life spacecraft, there are a number of programs under way. Those of most interest to broadcast satellites are listed in Table 2-2.

2.1.4 ADDITIONAL EFFORT REQUIRED

The selection of the design concepts and the implementation of the design will be important aspects of the broadcast satellite program. As described in the previous sections, there are numerous technology developments under way which can be applied to a broadcast satellite. However, it is important to realize that these developments are not likely to carry the technology to the state required by broadcast satellites. There remains useful work to be done to achieve the necessary confidence level for long life success for a 1973 launch. For example, the Boeing 20-watt per pound foldout solar array program has been very successful and has reached the point where its sponsor, NASA-OART, is evaluating whether or not the technology has matured sufficiently to achieve the goal of technology readiness. The GE 30-watt per pound roll-up array design is being developed under the sponsorship of JPL. Both systems are near the point where either could be selected for a flight program with confidence of technical and schedule success, although full-scale system fabrication and testing remain. The Hughes/AF LRSCA array program flight demonstration should take place in the 1970-71 time period. It is important, therefore, for the broadcast satellite program to identify areas of prime interest and insure that programs are under way in these areas.

The general aspects of reducing weight and improving solar cell performance are proceeding at a pace governed by the total Government space program; it is not necessary for the broadcast satellite program to do more than lend its support to this type of activity and provide inputs with respect to its general needs.

Due to the high labor costs associated with the manufacture of large solar arrays, a development effort to create an automated cell laydown technique could reduce the cost of array manufacture.

High voltage solar arrays should be investigated in order to determine the problems. limitations, and areas where work is needed. This work needs to be related to the tradeoffs of producing high voltage power at the solar array rather than stepping up the voltage with power conditioning equipment. High voltage arrays could permit cost and weight reductions and eliminate problems in the power conditioner.

Table 2-2. Currently Funded Efforts

Program	Contract No.	Sponsor	Contractor	Amount	Remarks
1. Advanced Solar Arrays					
a. Feasibility study of 30-watt-per-pound roll-up solar array	Phase 1 951969 951970 951971	JPL	General Electric Ryan Aircraft Fairchild Hiller	$167K $167K $167K	Phase 1 feasibility studies of 10 kW solar array system for interplanetary mission completed in July 1968.
	Phase 2 952314	JPL	General Electric	$ 811K	Phase 2 program to assemble an engineering prototype and subject it to a vigorous environmental test program is expected to be completed in early 1970. A full size demonstration of one element (of four) of the General Electric system is shown in Figure 2-1.
b. Large-area solar array program	951653 951934	JPL	Boeing Aircraft	$5.6M	Design of a 50 kW system comprised of four 12 5 kW subsystems for an interplanetary mission Selected design concept utilizes thin silicon solar cells, beryllium frames, and stretched fiberglass substrates Manufacturing methods have been investigated and environmental tests of elements of the system have been completed
c. Development of lightweight rigid solar panels	NAS 7-428	OART	EOS	$463K	Performance goal is 25 lb/kW. Design concept uses electroformed aluminum substrate, beryllium frames, and thin silicon solar cells. Prototype models being designed and constructed
d. Large retractable solar array	F33615-68C-1676	AF-APL	Hughes Aircraft	$1M	Design concepts for rollup solar arrays for power levels of 0.5 to 20 kW 2-axis solar orientation system to be provided A 1.5 kilowatt flight experiment is to be ready for flight by October 1970 Goal is 35 lbs/kW (array only) Laboratory testing to demonstrate 3 to 5 year component lifetime
e. Cadmium-sulfide thin film solar array development	NAS 3-11821 NAS 3-10605	NASA-Lewis	General Electric	$54.5K	Initial contract was to develop methods of interconnecting CdS solar cells into 25 cell modules that could be rolled on 2-inch diameter roll Second contract was to fabricate three 100-cell sub-panels
2. Solar Cell Development					
a. Improved CdTe solar cell and array environmental effects investigation	F33615-67-C-1485	AF-APL	General Electric	$341K	The objectives of this program are to produce a stable cell with an efficiency of 8% and cell weight of 0.02 pound per square foot
b. Improved solar cell contacts	NAS 5-11595	NASA-Goddard	Litton Industries	$ 56K	Research on the degradation of solderless Te-Ag contact silicon solar cells.
c. Photovoltaic radiation program	----	NASA	JPL	$224K	Determination of the radiation characteristics of lithium-doped solar cells.
d. Development of improved solar cell contacting techniques	952144	JPL	High Voltage Engineering Corporation	$44K	Analysis and development of a superior type of solar cell contact - interconnection combination
e. Cadmium-sulfide thin film photovoltaic cell development	NAS 3-9434	NASA	Clevite Corporation	$514K	Effort directed toward improving CdS film quality, cell efficiency, and stability.
3. Auxiliaries					
a. Brushless, direct drive solar array re-orientation system	NAS 5-10459	NASA-Goddard	Westinghouse Electric Co.	$49.8K	Development of control and logic circuits for use in the design of a brushless, direct drive solar array re-orientation system
b. Orientation linkage of a solar array	F33615-67-C-1785	Air Force APL	Hughes Aircraft Co	$283K	Development of the technology for actively orienting solar cell arrays with power requirements in the 0.5 to 20 kW power range for 3 to 5 years of mission life at altitudes ranging from 200 n m to synchronous altitude.

Deployment and orientation of arrays larger than 5 kilowatts present a spacecraft system design problem. It is important to investigate further the effects of solar array structural flexibility on the dynamics of the vehicle. Solar array flexibility is a function of array weight and, if flexible arrays cannot be accommodated by the stabilization system, an additional constraint is imposed on the array design that can have significant influence on weight. This interaction problem is a complex one and is a long lead-time item because a number of disciplines and subsystems are involved.

The two-axis drive subsystem should be investigated as a potential long-life reliability problem. The Nimbus 2 single-axis drive subsystem for a 500 watt array has been flying successfully for over two years. Despite the success of the array drive subsystem on this one satellite, there still remains a degree of uncertainty about the long-life reliability of such electromechanical drive devices. Furthermore, no large-panel, two-axis drive subsystem for arrays delivering powers over 5 kilowatts has ever been flown in space.

A continuing review of the projected requirements of broadcast satellites, coupled hopefully with a focusing on specific configurations with respect to solar array technology, is required. The long lead times associated with establishing a high confidence on the long-life reliability of a design should provide an incentive for early design selections.

2.2 HIGH POWER DC ROTARY JOINT

Transfer of direct current electrical power across continuously rotatable mechanical joints requires the use of rolling, sliding or liquid metal electrical contacts. The most widely used and highly developed power transfer device is the slip ring-brush combination. A rotary transformer concept for power conditioning might be employed to eliminate the need for a dc rotary joint for high voltage applications.

A typical spacecraft power slip-ring assembly is shown schematically in Figure 2-2. A round, conductive metal ring rotates with its supporting shaft. One or more conductive brushes mounted on the nonrotating member of the rotary joint slides against the surface of the ring to provide the electrical contact. The electrical circuit passes from the array through an insulated conductor to the inner surface of the ring; it then travels from the brush, which contacts the ring continuously, through another conductor to the load. The return path is identical except that a separate brush and slip ring are utilized to complete the circuit back to the power source.

2.2.1 GENERAL CAPABILITY

Low-power and medium-power slip rings have been tested in vacuum and successfully flown on operational spacecraft. These include the Nimbus, OSO, and classified space vehicles. A more frequent application of sliding electrical contacts in space has been the use of brushes for motor power commutation. Devices of this type have operated at low or medium power levels in a number of space applications. The achieved current levels, however, are far below the projected requirements of a broadcast satellite rotary joint.

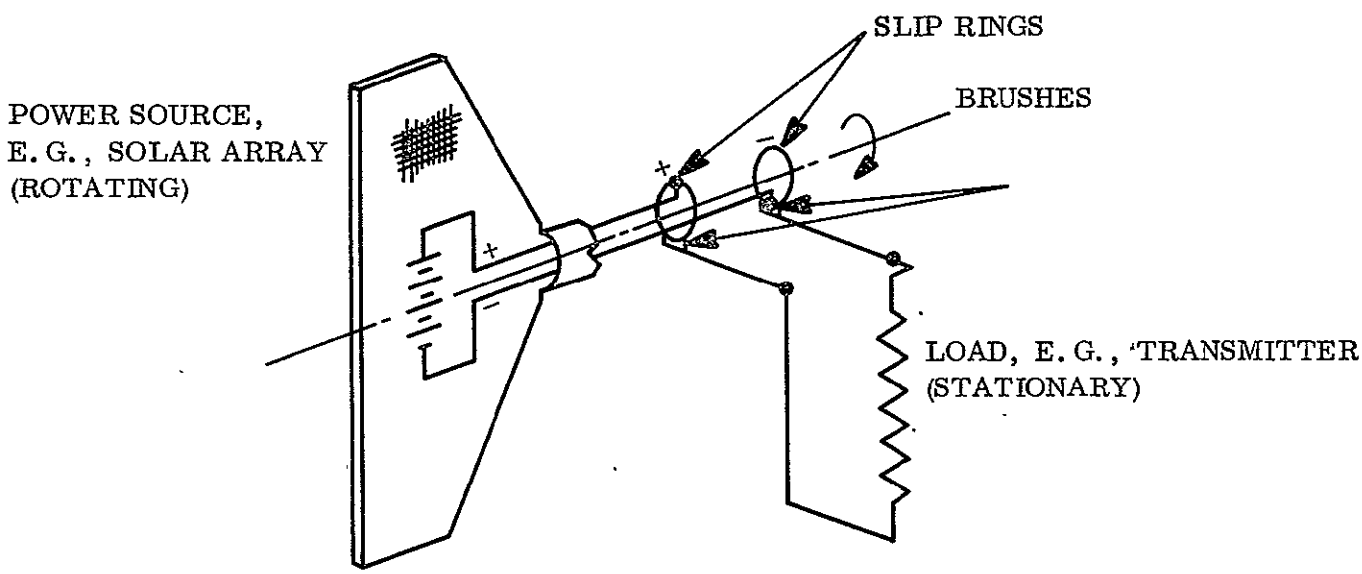

Figure 2-2. Typical Power Slip Ring Schematic

Results of reported applications or tests to date are as follows: Nimbus power slip-ring contacts carrying 10 amperes of current have accumulated approximately 10^4 feet of sliding wear during approximately 2-1/2 years of space operation. OSO slip rings, rated at 3.5 amperes, have operated for approximately 2.5×10^6 feet of ring-surface travel for approximately 8800 hours during one year in space.

In vacuum tests for ground based equipment, Clauss has operated power slip rings for 1.8×10^6 feet of surface travel, while conducting currents on the order of 4 amperes. (Current density peak was approximately 300 amp/in^2.) In these tests, the characteristic brush wear quoted is on the order of 10 mils of brush height reduction per 10^6 feet of lineal ring-surface travel.

The power transfer applications cited above all involve conventional voltage levels for space applications, i.e., in the range of 28 to 32 vdc. Thus, the added problems associated with high inter-ring voltages were not present in these evaluations.

2.2.2 MAJOR PROBLEMS

Rotary joints for various broadcast satellite applications under consideration have a broad range of potential operating conditions and requirements. For a 20 kW design power level, inter-ring voltages could range from 50 to 20,000 vdc, while corresponding series currents range from 400 amp. down to 1 amp. Rotational speeds also vary with possible vehicle designs, i.e., basic rotational speeds are either one revolution per day

(non-spinning vehicles) or 60 to 100 revolutions per minute (spin-stabilized vehicles). For purposes of comparison, a brush operating against a slip ring turning at 100 rpm will slide 1.44×10^5 times as far as the same brush would travel in the same time interval if the ring were turning at one revolution per day.

The major problems associated with the possible sets of operating conditions vary significantly.

Brush wear is proportional to surface sliding distance after run-in has been achieved. Therefore, brush life and wear-debris accumulation are vastly more severe problems (other conditions being equal) in the 60 to 100 rpm operating mode than at one revolution per day.

Brush heating is a function of contact resistance, current and current density, friction, lubrication technique, brush thermal conductivity and mass, ring thermal conductivity and mass, and a number of other factors. Brush temperature in turn affects the wear rate of both ring and brush, the mechanical durability of each, the bond strength and method of attachment of the brush to its mechanical support, the thermal compatibility of the ring with its insulating support and with the electrical conductor material, and the chemical stability and evaporation rate of the lubricating medium provided.

High voltage configurations of the rotary joint present other significant problems. The convoluted insulating surface which must be provided to prevent arc-over between slip rings adds significantly to the weight of the basic elements of the rotary joint. Another severe problem is the prevention of surface tracking due to insulator surface breakdown at high voltage due to contamination caused by brush debris.

Electron bombardment of insulator surfaces, which may result from arcing at the brushes, can cause the release and ionization of surface-adsorbed gas films which, in turn, can also bring about surface tracking under high voltage conditions. Both the gas production and the breakdown probability increase directly with inter-ring voltage levels.

Bearing lubrication presents significant problems, particularly at the higher rotational rates under consideration. In addition to intrinsic lubricant life problems, there may be considerations relating to the compatibility between brush and bearing lubricants, as well as thermal problems resulting from the brush heating noted above. Another significant problem may result from bearing contamination with brush wear debris. Minor contamination may degrade lubricant performance, while higher levels of contamination may result in excessive driving torque and, ultimately, in jamming of the bearings.

Material selection can be a problem area not only due to requirements for high dielectric strength or other special electrical or mechanical properties, but also due to the necessity to minimize the degree of outgassing and sublimation from material surfaces. Outgassing of adsorbed surface gases which occurs under vacuum conditions is a function of the type of material and the temperature. The partial gas pressures created could cause high-voltage breakdown at voltage levels lower than otherwise expected. Very little data is

currently available on outgassing and sublimation phenomena for the types of needed materials at the high voltages, high temperatures, radiation environment and vacuum conditions encountered in broadcast satellite applications.

2.2.3 CURRENTLY FUNDED EFFORTS

Current efforts in the development and evaluation of dc rotary joints are rather limited. Tests of narrow scope are being performed or are planned at TRW, LMSC, and Hughes for medium-power slip rings for use in future spacecraft. Evaluation of two brush-commutator material combinations was recently (1966-1967) performed at NASA Marshall Space Flight Center for an Apollo Telescope Mount torque-motor application. The program conducted at MSFC has involved sliding with conduction on motor commutators, and sliding without conduction on simulated commutators.

The only recently reported work (1965) directly applicable to the TVBS system is the self-lubricating, high-current, bursh material development program conducted by Clauss and others for Arnold Air Development Center. In this program, intended for a ground-based radiation simulator, a sintered brush of 82.5% Ag, 2.5% Cu, and 15% MoS_2 was found to be superior in low-noise characteristics and wear resistance to several other material combinations evaluated.

The only known tests currently being conducted are for various spin-stabilized spacecraft applications. No data is available, but significant failures are known to have occurred recently in simulation tests. In these tests, desired sliding wear life and power levels were less than those sought for broadcast satellite applications.

2.2.4 ADDITIONAL EFFORT REQUIRED

Review of broadcast satellite dc rotary joint requirements has resulted in the identification of several significant and necessary development areas shown in Table 2-3.

Table 2-3. Recommended Rotary Joint Technologies

• Materials selection - Brush - Ring - Lubricant (brush and bearing) - Insulation	• Thermal design
• High voltage design	• Operational considerations - Brush debris collection - Pre-operation bake-out - Programmed multiple brush use for wear compensation
	• New rotary power transfer device concepts

New concepts such as rotary transformers, rolling ring (non-sliding) and liquid metal rotary joints should be studied as a means of eliminating wear and heating problems, and reducing noise associated with sliding power-transfer devices.

2.3 HIGH VOLTAGE POWER CONDITIONING

2.3.1 GENERAL CAPABILITY

The power conditioner is the spacecraft subsystem which accepts the dc electrical power generated at comparatively low voltage by the primary power source (e.g., solar array), and converts it to the several regulated voltages and/or currents required to operate the various spacecraft electrical loads. Some of the major functions performed by the power conditioner could include line filtering, inversion from dc to ac, transformation of voltage amplitudes, filtering of ac ripple regulation, and overload and short circuit protection.

High level power conditioning refers to that portion of the power conditioner subsystem which is employed primarily to provide the high voltages and currents essential for the operation of the high power stages of the broadcast satellite transmitter, such as the final output amplifier. Typical inputs to the high level power conditioner from the solar array might be 28 to 300 vdc (depending on array design); typical outputs might range from 1,000 to 16,000 volts dc with regulation percentages between $\pm 0.05\%$ and 3%, depending on output tube requirements.

The technology for long-life, space-borne power conditioning equipment is well-known up to dc levels of approximately 1000 watts. However, no unclassified power conditioning hardware operating at power levels above 650 watts has yet been placed in orbit. The power conditioning system for SERT II, which is to be flown in the latter part of 1969, and has requirements for 1 kW at 3 kV (unregulated), contains some new concepts which may be used for the higher voltage levels.

These include open transformer and component packaging instead of potting (thus using the vacuum of space for insulation), and thermal control by bonding heat sinks to the integrated circuit boards and having oversized holes in the sink for leads. This subsystem weighs approximately 30 lbs/kW.

An operational spacecraft with a power level in the 500 watt range still in orbit is Nimbus II. Other examples of space hardware programs using powers up to this level are shown in Table 2-4.

A recent study by NASA/GSFC of over 70 satellite high-voltage failures concluded that almost 80% of the failures were due to poor design. Table 2-5 lists typical failures and the resulting design changes. Corona and arc breakdown were caused by improper selection of materials and components, by inadequate geometric orientation of piece parts, and by poor techniques for potting, foaming, encapsulation and conformal coating. These failures occurred at low power. High power plus high voltage is a potential for catastrophic failure in a satellite. The technical feasibility of high-power, high-voltage conditioners in the hard vacuum of space over periods of more than 2 years has yet to be shown.

Table 2-4. Typical Satellite Power Levels

Satellites Flown	Max. Input Power	Highest DC Voltage Used
Nimbus II	500 W	1300 Vdc
OAO	250 W, continuous 500 W, 10 minutes	1000 Vdc
ATS-D	175 W initially	600 Vdc (800 Vac) 3000 Vdc (ion engine)
Syncom	< 100 W	1000 Vdc
Early Bird	< 100 W	1500 Vdc

Table 2-5. Typical Satellite High Voltage/Low Power Levels

Probes or Satellites Flown	DC Voltage At Low Power	Failure	Design Fix
Nimbus	1000 Vdc	Arc in harness and connectors due to entrapped gas	Separate high voltage cables, used new connector insulation.
Mariner IV	1200 Vdc	Arc punctured insulation in TWT terminals	Changed geometry and improved encapsulation
Mariner IV	2800 Vdc	Arc due to trapped gas in power supply	Used stycast in place of foam
Explorer	5000 Vdc	Arc in connector due to entrapped gas	Improved potting techniques
Agena	1650 Vdc	Arc in radar transmitter caused by outgassing of silicone grease	Pressurized the transmitter
SERT I	5000 Vdc	Corona in connector caused treeing, resulting in an arc	Use vented connectors with out potting
Javelin	15000 Vdc	Corona caused by trapped outgassing in plasma detector	Changed potting material and vented detector case

General industrial capability mirrors that shown in Tables 2-4 and 2-5 quite closely. The equipments which most nearly approximate the broadcast satellite requirements are power conditioning apparatus for aircraft (in particular, the high power systems used for radar modulators in high performance, high altitude aircraft). Here, the power and voltage levels may be closer to broadcast satellite requirements than present spacecraft designs; however, satellite environmental requirements will not have been considered in designing for aircraft applications.

2.3.2 MAJOR PROBLEMS

The feasibility, performance, and long-life reliability would be improved by the application of additional R&D effort. The technologies leading to high-voltage design which minimizes the probability of electrical breakdown are technologies for which feasibility is yet to be established. A separate discussion of the critical technology associated with the handling of high dc and ac voltages may be found in Section 2.4.

Determination of the maximum modular size of the power transformer in such a power conditioner and the generation of multiple high voltages for transmitter output devices are also considerations involved in solving the feasibility, performance (e.g., efficiency), and reliability problems. Special load requirements may have to be considered in determining the maximum size for power conditioner modules. For example, a multi-collector, high-power transmitter tube which requires a number of steps of high voltage for proper operation may well determine the quantity, power output, and size of the conditioner modules.

High voltage power conditioning is an important technology because a large percentage of the weight of the broadcast satellite is in the power subsystem. To get the best combination of power conditioner and solar array, a tradeoff between solar array weight and power conditioner weight must be made. System analyses should be performed to determine whether it is better to build a highly efficient but heavy power conditioner (and thus reduce the solar array size) or to accept higher power-conditioner losses and/or a larger solar array in favor of reduced power conditioner weight.

2.3.3 CURRENTLY FUNDED EFFORT

A survey of currently funded efforts uncovered only items designed primarily for low-power and low-voltage applications. Very few studies are in progress which might be applicable to the high-power, high-voltage, and long-life requirements of a broadcast satellite.

Representative examples of recent or current contract efforts are:

1. Design of a Multi-kilowatt Photovoltaic Power System for Manned Space Stations (NAS 9-5266).

2. Power Conditioner for Experimental Model, SERT II Ion Thruster (NAS 3-7939).

3. Analysis of Aerospace Power Conditioning Component Limitations, Solar and Chemical Power Systems (NAS 7-546).

Current effort fails to provide the required power conditioner information in two respects; first, the power and voltage do not approach the levels required for a TVBS system; second, the simultaneous combination of high power and high voltage has not been investigated.

2.3.4 ADDITIONAL EFFORT REQUIRED

More study and experimentation are required to determine the effects of outgassing, hydrolysis, and thermal degradation on voltage breakdown of materials at low gas pressures. An extensive report containing technical papers on the voltage breakdown problem can be found in JPL Technical Memorandum 33-280, "Proceedings of the Workshop on Voltage Breakdown in Electronic Equipment at Low Air Pressures," dated December 15, 1966. High voltage breakdown is a very critical problem in components and devices. Voltages from 327V to 50,000V can cause failure by corona; they can also cause breakdown through gases, as predicted by Paschen's Law. These problems are covered in Section 2.4 on High Voltage Handling.

Determination of the maximum hot-spot temperature for long-life operation and optimum materials to be used in magnetic devices both need considerable attention. (Standard transformers generally operate at maximum hot-spot temperatures between 105°C and 220°C). It is necessary to determine the best thermal-radiating fin size, shape, weight, and temperature versus the best power conditioning size, shape, weight, temperature, and efficiency. This study is extremely complex due to the large number of variables. Some of the interactions between variables are inadequately known at this time, although much is known about most of these variables. Thus, with some reasonable assumptions, a parametric analysis should result in optimum configurations for both the thermal-radiating fin and the power conditioning equipment.

Trade-off studies are needed to obtain the best combination of designs for the power conditioner components, thermal control, solar array and dc rotary joint. Thus, additional development effort could have an impact on the broadcast satellite system in terms of improving system performance, reducing weight and proving the technical feasibility of large, high-power, high-voltage power conditioning subsystems in the vacuum of space.

2.4 HIGH VOLTAGE HANDLING

2.4.1 GENERAL CAPABILITY

Various subsystems of the broadcast satellite systems will have to be designed to generate, conduct, or otherwise handle high voltages, either dc or ac (up to RF). For some foreseeable applications, voltage levels may go as high as 20,000 volts. The primary areas of the system where high voltages may be present include the solar array (in cases where no separate power conditioner is used), the dc rotary joint, the power conditioner, possibly an RF rotary joint, and the final output stage of the transmitter.

Many types of voltage breakdown phenomena (glow, corona, arcing, tracking, treeing, etc.) are known to exist. Generally, breakdown is a function of factors such as the nature and geometry of the materials present, the voltage level, the frequency of the voltage, the

temperature, the pressure of any gases present (either through intentional use or as the result of outgassing), the condition of the surface of the material, and the distance between conducting electrodes or surfaces. The importance of material selection to avoid breakdown is immediately evident from this series of factors.

Most materials suitable for ground-based systems cannot be used, a priori, in space-borne systems because the effects of hard vacuum seriously alter material performance. Outgassing and sublimation phenomena under vacuum conditions lead to such problems as arc-over and corona which, in turn, can short out electrical systems and, in addition, can cause reduction in attained performance levels of materials. These problems are aggravated in high-power systems because of the elevated operating temperatures of various components which tend to cause more rapid deterioration of the insulating and dielectric materials and the production of large volumes of outgassing and sublimation species.

Some empirical work has been accomplished regarding the outgassing of dielectric materials, but direct application of the available data to broadcast satellites cannot be made. The two major drawbacks in applying this data are: (1) experiments have been conducted at relatively low temperatures, generally below 150°F, and (2) no system analyses have been conducted to establish the exact magnitude of the problem in terms of various system operating parameters and geometries.

2.4.2 MAJOR PROBLEMS

The outgassing of materials in vacuum poses other electrical problems besides the change in properties of the insulation materials. These problems are related to high-voltage, electrical breakdown phenomena. For example, the impaired performance of the OSO I and II satellites was attributed to high voltage breakdown because of inadequacies in insulation and improper venting, degassing and materials selection.

Because of the outgassing phenomenon under vacuum conditions, a small partial gas pressure may build up which could cause a breakdown in a high-voltage system. In general, as the pressure between a given pair of electrodes decreases, the voltage necessary to initiate a discharge decreases to the minimum predicted by Paschen's Law. At pressures below this Paschen minimum, the voltage required to cause an electrical discharge increases as pressure decreases further. Thus, when operating in a hard vacuum condition, outgassing can raise the gas pressure and cause breakdown as the pressure adjacent to piece parts approaches the Paschen minimum voltage point.

There are special cases where strict adherence to Paschen's Law predictions for air may give unexpected results. Ordinarily, the minimum sparking or breakdown potential in air (for parallel plate electrodes at, say, a 1 mm spacing and a pressure of 5 torr) is 330 volts. However, this voltage varies considerably for gases other than air and for different electrode shapes. Also, where electrodes are near surfaces of potting compounds or other types of material prone to outgassing and development of surface charges, the minimum breakdown voltage will generally be reduced. The proximity of

surfaces with polar molecules can provide lower energy paths of conduction than would be predicted by Paschen's Law calculations for parallel plate separation and gas pressure factors.

Since a broadcast satellite will not be required to operate in the critical altitude region (60,000 to 310,000 feet), measures should be taken to prevent the high voltage equipment from being energized until a hard vacuum has been attained inside the vehicle. The hard vacuum of space has a very high dielectric strength; thus, open type (unencapsulated) construction becomes a promising technique provided that outgassing, multipacting and sublimation effects can be avoided, and adequate thermal dissipation can be effected.

Equipment must be designed to avoid high voltage stress areas which could produce corona. Corona can jam or block the very sensitive electron devices necessary for broadcast operation. Equipment must also be designed to avoid dielectric discontinuities, prevent voids in encapsulants, use non-tracking insulations, prevent condensation, avoid pointed electrodes, use low dielectric-constant insulators, use proper air gap length, dampen inductive switching surges, and prevent sublimation or evaporation of conductive materials.

Multipacting failure does not occur in power conditioning equipment. However, in the RF sections of the broadcast satellite system (e.g., circuits, connectors, coaxial lines, microwave components, waveguides, antennas, etc.) the proper combination of conditions may exist which will support a multipacting discharge. Much information is already available on the interaction of RF voltage amplitude, electrode spacing and applied frequency, and on combinations of these conditions with electrode configurations and materials which will produce a multipacting discharge. Much of the work to date is on parallel plate electrodes or is based on experimental data, because electron trajectories and electron distributions between complex electrode configurations (with non-uniform fields) do not lend themselves easily to rigorous analysis. Much work is still needed to predict possible multipacting breakdown with real hardware configurations and materials. Also, effort is needed to further investigate the degree and nature of the various deleterious effects due to multipacting (e.g., deterioration of the emitting surface, change in circuit impedance, detuning, noise content, non-linear effects), and the effectiveness and implementation of various techniques for eliminating multipacting.

2.4.3 CURRENTLY FUNDED EFFORT

A review of high voltage handling technology is being performed at GE under the Multi-kilowatt Transmitter Study for NASA/MSFC (NAS 8-21886). Program task objectives are to identify and characterize materials for specific pertinent areas of application in high-power, satellite-borne transmitters and associated power conditioners. The results of the program will be an identification of critical problem areas and suggested solutions.

The SERT II program has requirements for a 1 kW, 3 kV (unregulated) power conditioner for energizing an ion engine. In addition, Hughes Aircraft has been developing a 3 kW, 2 kV power conditioner for JPL for operation from a solar array. This conditioner is also to be used to operate an ion engine in space.

2.4.4 ADDITIONAL EFFORT REQUIRED

Both system and subsystem analyses are needed to establish the magnitude of the problems described here. In addition, basic empirical data concerning sublimation and outgassing rates for typical materials used at nominal operating parameters in these systems is required. Numerous methods have been employed to determine the effect of outgassing materials condensing on other surfaces. Some have attempted to simulate hardware geometry, while others have used a direct line-of-sight criterion. Data obtained in this fashion cannot be generalized to other cases because of the possibility of reflection of outgassing particles from other surfaces. The recently developed "distribution box" technique for acquisition of condensation data would make it possible to analyze the condensation phenomenon for any geometry.

The distribution box technique is a material test method in which outgassing products from a material sample heated by radiation from the inside walls of an electrically heated cylindrical box are directed through two holes in the bottom of the box. After passing through the holes, the outgassing products are collected as condensate on two cooler mirrors; the weight gain of the mirrors is measured as a function of time so that the degree of outgassing can be assessed for this sample and deduced for other geometric configurations.

Concurrently with material selection, testing, and evaluation, the basic design philosophy must be analyzed and resolved. Several possible design approaches should be assessed. These include: the use of a system hermetically sealed with dielectric gas, liquid or solid; the enclosure of all high voltage parts or components in vacuum cast encapsulations; designing the system for operation only in hard vacuum, with provisions to control sublimation, limit outgassing and prevent energizing of the high voltage unless hard vacuum exists.

2.5 GRIDDED TUBE TRANSMITTER

There are several requirements which may dictate the use of UHF for certain broadcast satellite systems. For these applications, the high-power gridded tube is a simpler device which is several years ahead in development than high power microwave tubes. Several high efficiency circuits are available which make gridded tube transmitter efficiencies competitive with microwave tube transmitters.

2.5.1 GENERAL CAPABILITY

Present gridded-tube transmitters with capabilities for transmitting TV type video-modulated signals employ Class B linear amplifiers. Unfortunately, this type of final amplifier is relatively low in efficiency (e.g., 43%) when used for TV type transmission. Until now, there has been little demand for higher efficiency, high-power gridded tubes in space-environment applications.

Available tubes can provide good efficiencies either at low RF power levels (under a kilowatt) or at low frequencies (under 700 MHz). For space missions requiring multi-kilowatts of power at 800 to 900 MHz new tubes like the GE L-64S presently under development are needed.

Weights and costs of gridded tube transmitters are substantially less than for solid state transmitters due to the high output power and small size of a typical gridded tube. The 2.5 kW L-64S gridded tube shown in Figure 2-3 is approximately 1 inch in diameter and 1-1/4 inches long, exclusive of any cavity.* From the standpoint of best efficiency, modular construction is recommended only at power levels above 2.5 kW.

Based on recent life tests in cathode fabrication techniques, the cathode life of a gridded tube is expected to be five years. Reliability will also be substantially enhanced by a bonded grid technique in which the grid is physically joined to the cathode through an insulator, thereby eliminating the possibility of grid-to-cathode electrical breakdowns.

2.5.2 MAJOR PROBLEMS

A major problem in gridded tube design has been grid-cathode shorting. However, new techniques have been developed which improve the tube operation by a substantial margin. The most significant of these techniques involves the bonding of the grid to the cathode structure which will eliminate grid-cathode shorting problems, and should provide a very high transconductance of the order of one mho. This will result in higher gains and efficiencies.

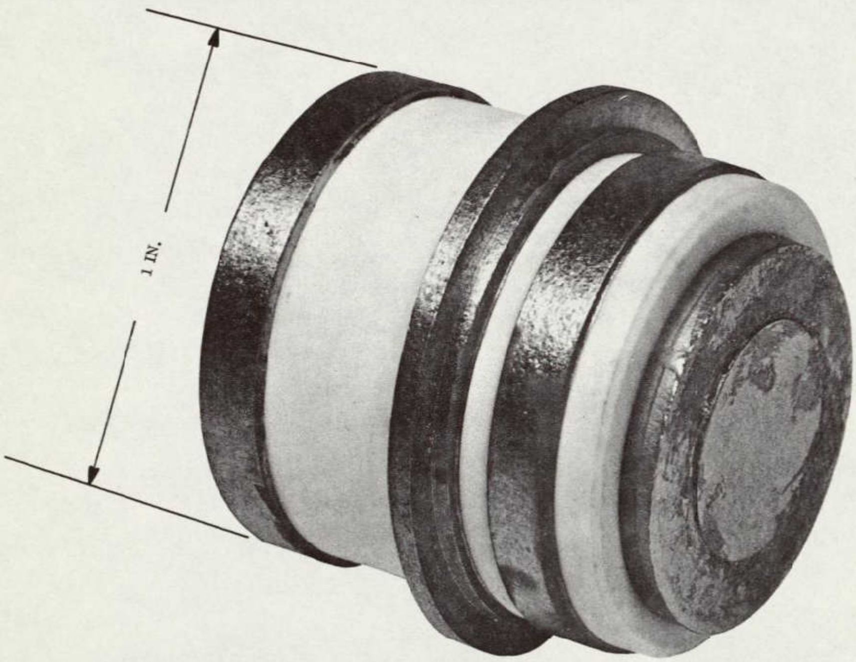

Figure 2-3. 2.5 to 5 Kilowatt GE L-64S Gridded Tube

*Including a UHF output cavity, the over-all size might typically be 6 inches in diameter by 2 inches long. An input cavity is also required.

A second problem area is material selection for the external cavity required by the gridded tube. Materials effects are of primary concern since they influence electrical breakdown characteristics in the very high vacuum of space. Multipacting is probably the most serious cause of breakdown in the RF cavity. Gridded tubes should be used in a high efficiency configuration rather than in a Class B linear amplifier. For AM modulation, peak efficiency would not be greatly improved, but average efficiency would be substantially increased by using the gridded tube in a high efficiency circuit. The comparison presented in Table 2-6 indicates the efficiency values for the higher efficiency configurations.

Table 2-6. Efficiency Comparison for Gridded Tube Amplifier (AM Modulation)

Circuit	Peak Efficiency	Average Efficiency*
Class B Linear	60%	43%
Doherty Type	65%	62%

*Average efficiency is based on an average signal power level of 32% of peak sync power in a TV AM modulated signal.

Thus, a high efficiency circuit, probably a Doherty type as in Figure 2-4, should be investigated further for a TVBS application at UHF.

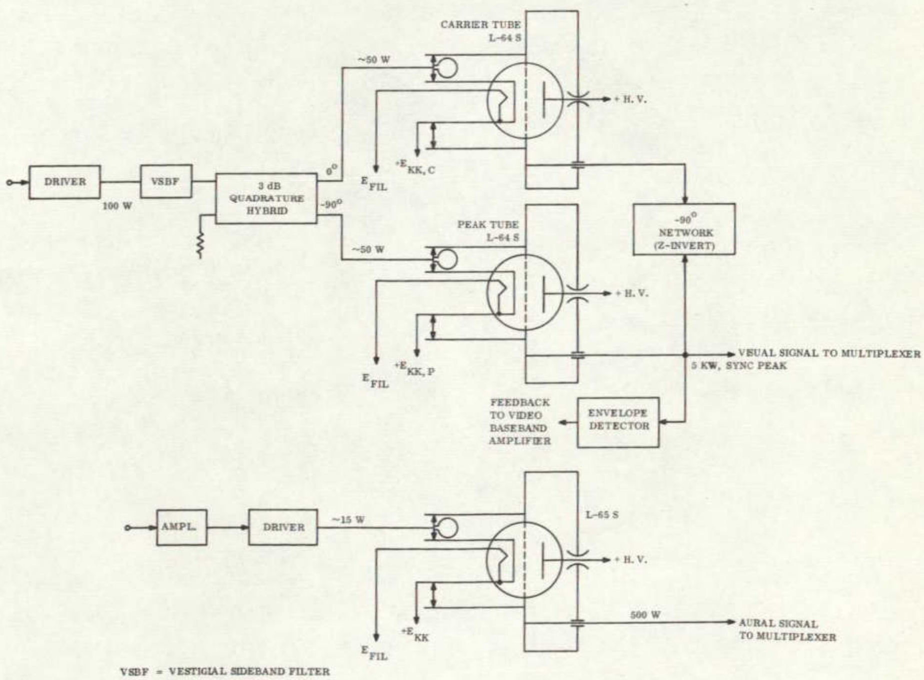

Figure 2-4. 5 kW UHF TV Transmitter Channel Using a Doherty Circuit for the Final Video Stage

2.5.3 CURRENTLY FUNDED EFFORT

The L-64S tube has been developed with GE funds between 1965 and 1969, and is presently undergoing a final test. Assistance in the development is being derived from parallel contracts with the Signal Corps, Contract DA-28-AMC-02483 (E).

Under the Multikilowatt Transmitter Study (NASA MSFC Contract NAS 8-21886) a breadboard version of the Doherty type UHF amplifier for AM-TV application is being constructed and tested. The purpose of this effort is primarily to show feasibility, but additional requirements not included in this effort must be considered ultimately.

2.5.4 ADDITIONAL EFFORT REQUIRED

Additional efforts are required to extend the L-64S tube development to include the advanced concept of the bonded grid. This will result in a gridded tube equal or superior to any other UHF tube in terms of stability and performance for UHF-AM applications.

Effort in evaluating and developing components specifically for space would consider the various materials effects on electrical operation, and also weights, sizes, and costs where unusual situations exist, such as for vestigial sideband filters.

Developing and evaluating high efficiency circuits is a requirement for the application of gridded tubes to high-power operation of the circuitry, linearization (if required), and integration of thermal control techniques with the electrical and mechanical design.

2.6 MICROWAVE TUBE TRANSMITTER

For those broadcast satellite mission requirements which dictate frequencies higher than UHF, the microwave tube transmitters would be selected. Three candidate microwave devices are candidates for the transmitter: 1) the klystron; 2) the crossed field amplifier (CFA); 3) the traveling wave tube (TWT).

2.6.1 GENERAL CAPABILITY

At the present time, there is one traveling wave tube (Watkins Johnson TWT type WJ395) in the 100-watt range which is qualified for space operation. Otherwise, only low-power space tubes are available.

Several NASA tube study contracts represent the most advanced status of microwave devices, and will dictate the nature of future transmitters. The initial studies are complete, and follow-on contracts will provide laboratory confirmation of study results. The contracts are as follows:

NAS 3-9719	Hughes	Design of Space TWT
NAS 3-11513	Litton	Design of Space CFA
NAS 3-11514	GE	Design of Space Klystron
NAS 3-11515	Litton	Design of Space ESF Klystron
NAS 3-11516	SFD	Design of Space CFA

There is no firm indication of any effort being expended on development of space-qualified, high power RF circuitry, which represents another major problem area. Thus, the above studies in conjunction with certain related thermal control studies appear to represent the present state of microwave transmitter development for high-power space applications.

Table 2-7 lists the predicted efficiencies for some of the tube types being studied. If development of these tubes is continued, they could be available and qualified for space transmitters in about 3 to 5 years.

Table 2-7. Predicted Efficiencies of Microwave Tubes

Tube Type	Type of Operation	Predicted Efficiency
CFA	UHF FM	80%
	UHF AM	70% (average)
	S-Band AM	60% (average)
TWT	S-Band FM	80%
	X-Band FM	75%
Klystron	S-Band FM	
	• Electromagnetic Focus	80%
	• Electrostatic Focus	75%
	X-Band FM	75%

2.6.2 MAJOR PROBLEMS

The major problem is the development of a high frequency tube to provide a high-power signal with high efficiency. Tube studies are progressing, but results cannot be well assessed until some experimental test data is forthcoming. In considering the tubes themselves, a significant problem with the large UHF TWT and klystron types concerns mechanical fabrication to insure compatibility with launch and orbit environment requirements. High frequency tubes encounter problems resulting from constrained beam sizes.

The attainment of the high efficiencies predicted is dependent upon the performance of multistage depressed collectors (4 to 20) and upon the use of voltage jumps in the case of the TWT. Efficiencies without depressed collectors range from 55 to 70 percent at saturation. Where many collector rings are postulated, the weight, size, and complexity of the power conditioner would increase significantly.

With each tube type, there is the problem of thermal dissipation. All the tubes under development have mechanical configurations dictating the use of heat pipes, which are not only custom-designed for the particular tube but which are also an integral part of the tube design.

It should also be noted that the operational standards already established for distribution satellite services are not necessarily applicable; therefore, new circuits, concepts, and propagation and operating phenomena peculiar to broadcast satellite applications will need to be investigated to determine standards and circuit specifications.

In the realm of circuitry for microwave transmitters, the circuitry will be an assembly of components which must retain a low overall VSWR and phase distortion characteristic to insure TV performance within distortion standards (such as EIA RS-240). The problems are more serious and not as well understood for FM transmission, where wide bandwidths of 30 to 60 MHz are required, especially since TV picture phase and amplitude linearities must still be maintained. To determine circuit performance in practice, a monitor subsystem including sensors for VSWR, power flow, and electrical breakdowns is required as an integral part of the circuitry. The circuitry to include these devices, with techniques to correct for faults, is sufficiently undefined to constitute a major area of effort in implementing a space TV transmitter.

2.6.3 CURRENTLY FUNDED EFFORT

The major effort in direct contracts for microwave transmitters are the five NASA contracts noted previously, each of which is described below. In addition, the Multikilowatt Transmitter Study (contract NAS 8-21886) includes applications of these tubes to transmitter configurations, and will also include a study of the high-power RF component problem.

2.6.3.1 Space-Borne Axial Injection Crossed Field Amplifier (NASA Contract NAS 3-11516; Report CR 72393)

An analytic study program to produce an optimum design of an axial injection crossed field amplifier to be used as the output stage aboard a broadcast satellite has been carried out by SFD Laboratories. The design was optimized with respect to highest efficiency, minimum weight, and minimum size while insuring the required lifetime and the meeting of other requirements such as the bandwidth, signal-to-noise ratio, linear dynamic range, and phase linearity specifications. The designs are for AM modulated tubes capable of providing peak sync output powers of 7.5 kW and 5.0 kW at 890 MHz and 2 GHz, respectively.

A trade-off analysis was performed to find an optimum combination of design parameters. Several concepts for a multi-stage collector were evaluated and a design with inherent field suppression of secondaries has been made.

The expected efficiencies are 80 to 85 percent at saturation and 60 to 70 percent at the average signal level. The multi-stage collector assumes a great importance in preserving high efficiency at the reduced drive levels encountered under AM operation. This is particularly true since the concept of RF control of the input current was not found to be of practical importance in this application. The collector will have 10 to 15 stages, the potential at some of the stages being below that of the cathode. The latter stages will require special power conditioning. Tube cooling is to be accomplished by the use of heat pipes.

This tube utilizes new approaches for the injection gun and the collector. However, since the slow wave structure parameters were not obtained by direct measurement, the direct experimental verification of the predicted performance is viewed mandatory. Of particular importance are demonstrations of high efficiency at reduced drive levels and a linear dynamic range of 20 dB.

2.6.3.2 Space-Borne Linear Injected Beam Crossed Field Amplifier (NASA contract NAS 3-11513; report CR 72392)

This study by Litton Industries involved an analytic program to produce an optimum design for a linear injected beam CFA to be used as a broadcast satellite output stage. The size, weight and efficiency of the design were optimized while meeting other performance specifications. The design is for a 2.0 GHz FM modulated tube with a power output of 5 kW.

A large, signal computer simulation of the interaction was employed to evaluate various efficiency enhancement techniques and the tube performance. A computer analysis was used to optimize the design of a multi-stage collector which includes field suppression techniques for secondaries. An over-all efficiency, in excess of 80 percent, was obtained by the combination of a moderate electronic efficiency, in the 50 to 60 percent range, and a 16-stage depressed collector. The four stages with potentials below that of the cathode will require special power conditioning. Tube cooling is to be accomplished by the use of heat pipes.

Although a number of efficiency enhancement techniques, such as phase focusing by field shaping, pre-bunching and potential limiting, have been evaluated and found to be favorable, the design does not rely on these techniques. Moreover, the slow wave structure parameters are based on direct experimental measurements. Consequently, while experimental verification of the predicted tube performance is still required, a relatively high degree of confidence is associated with this design. Direct experimental verification of the predicted performance with multi-stage collectors, however, is viewed mandatory.

2.6.3.3 Space-Borne Electrostatically Focused Klystron Amplifiers (NASA contract NAS 3-11515; report CR 72449)

Litton industries has recently completed a seven-month study program to develop the theoretical designs of space-borne, electrostatically focused klystron (ESFK) amplifiers. These tubes were required to transmit AM and FM television signals. The peak sync power for the AM tubes was to be 7.5 and 5.0 kW (at 0.85 and 2.0 GHz, respectively). The saturated output power for the FM tubes was to be 5.0 kW (at 2, 8 and 11 GHz).

At the inception of this contract, the state of the art for ESFK's was represented by two Litton ESFK's. The L5101 provides 1 kW CW at 2.3 GHz with an efficiency of 49% and the L5182 provides 1.2 kW CW at 4.4 GHz with an efficiency of 44%. These klystrons operate without collector depression.

Primary emphasis was placed on the problems of obtaining high efficiency and adequate heat transfer while maintaining long operating life, small size and low weight. The contractor investigated velocity jumps, extended interaction resonators, low perveance electron beams (0.5×10^{-6} perv), and multistage collectors. Mechanical and thermal studies were also performed. A combination of the above components and parameters was selected in an attempt to maximize over-all efficiency. This combination was translated into complete electrical and mechanical designs for tubes at 0.85, 2.0, and 11.0 GHz. Designs at other frequencies and power levels could be obtained by scaling techniques. These tubes were deliberately designed with a relatively low electronic efficiency (30%) to reduce the velocity spread of electrons in the spent beam. This was done to facilitate the use of depressed collectors.

A transverse magnetic field collector promises a better solution to the efficiency problem than previous designs by recovering a larger portion of the unused beam power. It is now estimated that ESFK's could be built with efficiencies* from 81% for the 0.85 GHz case to 74% for the 11 GHz case, utilizing the transverse collector scheme.

Direct experimentation to verify certain critical areas of the design is yet to be performed.

2.6.3.4 Space-Borne Traveling Wave Tubes (NASA Contract NAS 3-9719; report CR 72450)

An analytical study program to develop the theoretical design of traveling wave tubes has recently been concluded by Hughes Aircraft. AM and FM applications were considered in a frequency range from UHF to 11 GHz. The program was primarily directed to explore concepts and techniques for advanced design and performance. Such an approach was necessary, since the intended application for a broadcast satellite transmitter becomes feasible only when such advanced performance can be achieved at the time of a launching (e.g., in 1975). A number of concepts and design approaches have been evaluated for the tube design. With these new methods, it appears feasible that the tube performance can be very substantially improved compared to the present state of the art.

A major part of these advanced features is concerned with improving the efficiency. This is one of the most important factors (in addition to reliability and long life) in deciding whether such a system can be developed. The studies have shown that tube efficiencies in the range of 70 to 80% are possible. This compares to 50 to 60% efficiencies demonstrated on experimental traveling wave tubes, and 30 to 40% efficiencies on commercially available tubes.

Dielectric loading is being recommended for weight and size reduction of the UHF and S-band designs.

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*Based on average picture power

However, some of these new concepts have not yet been used in traveling wave tubes. Before these methods are incorporated into a traveling wave tube design, they have to be evaluated experimentally to determine their limitations and to establish design procedures for them. Among the concepts, the following are considered the most important and critical:

1. Multi-voltage jump taper. This efficiency enhancement method has been derived and evaluated with a large signal computer program for traveling wave tubes. The computer program is well proven and has provided useful and accurate analysis for similar methods in the past. However, this scheme has not yet been demonstrated experimentally.

2. Multi-stage collector depression. The multi-stage collector design incorporates several new concepts:

   a. Magnetic refocusing of the spent beam to improve the velocity sorting efficiency.

   b. Transverse magnetic beam deflection also to improve the velocity sorting efficiency.

   c. Electrostatic potential barrier on collector electrodes for improved suppression of secondaries.

3. Traveling wave tube modulator. The essential components and devices of the traveling wave tube modulator are within the present state of the art. However, the design concept requires experimental evaluation to determine its limitations.

2.6.3.5 Space-Borne Magnetically Focused Klystron Amplifiers (NASA Contract NAS 3-11514; report CR 72461)

An analytic study of magnetically focused, space-borne, klystron amplifiers for potential use as output stages aboard broadcast satellites has been performed by General Electric. The study covers a frequency range from UHF to 12 GHz in AM and FM applications. The study stresses high efficiency designs while maintaining long-life capabilities, low weight and size, and employing heat pipe cooling. An accurate and detailed large signal computer simulation of the interaction was employed to develop designs having electronic conversion efficiencies in excess of 60% before collector depression. The designs also met other requirements for gain, phase linearity and bandwidth.

A collector design was proposed which effectively suppresses secondaries and indicates high efficiencies of recovering the unspent energies of the beam. Over-all tube efficiencies in excess of 80% for FM and 60% for AM in television service are estimated. The tubes are designed for an optimum perveance of 0.5×10^{-6} and employ confined-flow solenoid focusing of 2 to 3 times the Brouillon value to secure low interception under large signal conditions and to provide a good entry into the depressed collector. The amplifiers are cooled by heat pipes and are of rugged construction.

Although the designs are based on a sound foundation, none of the concepts have been evaluated experimentally and a verification of the interaction process, focusing schemes, collector operation and later of heat pipe cooling is viewed mandatory.

2.6.4 ADDITIONAL EFFORT REQUIRED

The tube studies should be continued into the prototype stage to better determine the characteristics that will be realized in practice. Linearity and power supply requirements for AM operation and efficiency for all tubes in all applicable frequency bands are of major significance.

High power RF technology should be expanded: This will frequently be concerned with the design of custom components for specific tubes to obtain the proper impedances, operating power levels, bandwidth characteristics and such other factors as the system and mission studies indicate.

Supporting techniques which are vitally related to the transmitter development and also need further development effort include those in the power conditioner area, particularly for the multiple-collector type tubes. Thermal control is also of concern especially where efforts are leaning toward a heat pipe designed as an integral part of the tube, both for initial heat transfer and for interfacing with the external heat sink.

Microwave transmitter circuits need to be developed further for low VSWR, amplitude distortion and phase distortion across wide bandwidths, and for required fault monitoring and automatic correction.

2.7 HIGH POWER RF COMPONENTS

2.7.1 GENERAL CAPABILITY

Radio frequency components used in a high-power braodcast satellite transmitter include devices such as multiplexers, vestigial sideband filters, power combiners, circulators, RF filters, tuned circuits and similar items. Little has been published on the problems and solutions for high power RF components for use in space transmitters. Presently, most RF components in space applications operate either at low voltages (under 300 volts) or under pressurized conditions so that the materials effects which occur at high voltages in space do not appear. The potential breakdown conditions in space include the phenomena of outgassing, multipacting, dielectric breakdown and sublimation, any of which can cause operational failure unless eliminated.

Related problem areas include the adequate design of monitor and protection circuitry to indicate abnormal operating conditions and to prevent damage from RF breakdown.

2.7.2 MAJOR PROBLEMS

Electrical breakdown is characterized by arcing, corona, and dielectric deterioration. These effects, in turn, are determined by the action of materials in a high vacuum. Thus, the problem involves an evaluation of materials, the effects of these materials when acted upon by electrical fields, and the integrated effects of materials and fields upon RF components.

Large size and weight normally dictated by the high power levels at which the components must operate represent another problem for power combiners, frequency multiplexers, and vestigial sideband filters (required for AM-TV operation). The larger size and weight are generally due to the need for greater power handling capability without breakdown and for the addition of thermal radiating fins to dissipate heat more effectively. The size and weight of ground based RF components of these types are generally unacceptable for space operation. Consequently, a component selection or design approach which provides the necessary performance while minimizing undesirable mechanical features is required.

Thermal control of RF components has generally been ignored. On the earth, convection provides some cooling effects. In space, the power absorbed in the RF lines and components can only be dissipated by conduction to a heat sink radiator or by direct radiation to space.

2.7.3 CURRENTLY FUNDED EFFORT

The only known funded effort on the specific problem of high-power RF components in space is the Phase II Program of the MKTS contract (NAS 8-21886). Those aspects of the high RF power problem (up to 1 kilowatt per channel) involving the antenna system are being studied under NASA contracts NAS 3-11524 and NAS 3-11525 which were started early in 1969.

2.7.4 ADDITIONAL EFFORT REQUIRED

Efforts are required in several areas to ensure the satisfactory performance of the RF section of a space transmitter. The initial area requiring better definition is an extended study of how materials are affected at high temperatures in the presence of high intensity RF fields. An identification and evaluation of the best materials, processing techniques, and supplementary techniques to minimize the possibilities of an RF voltage breakdown are needed.

Following the identification of optimum materials, a subsequent area for additional effort should be the design of RF components with minimum size and weight. This should be considered when the transmitter RF circuit requirements are reasonably well established so that the feasibility of developing new components specifically for space systems can be determined.

Other areas requiring additional effort include component design using integrated thermal control techniques. In general, this can be performed initially as an RF component study, and then integrated with a transmitter system study in future programs.

2.8 RF ROTARY JOINT

2.8.1 GENERAL CAPABILITY

The general performance capability of high-power RF rotary joints operating in the hard vacuum of space (required for anticipated TV Satellite missions) is not known. At present, the only barometer that can be used to attempt to assess the capability is the data that exists from ground tests. Table 2-8 lists typical rotary joint types that might be utilized at a given power level and frequency band.

Table 2-8. Typical Types of Rotary Joints

Average Power (kW)	UHF	Frequency Range S-Band	X-Band
0.5	In-line coax	In-line coax	W.G.
5.0	In-line coax	W.G.	W.G. (TM_{01})
25	In-line coax	W.G. (TM_{01})	-----

Here, W.G. means that the input and output ports are rectangular waveguides and the rotating section is coaxial; W.G. (TM_{01}) means that the input and output ports are rectangular waveguides but the rotating section is circular waveguide. If data from ground-based tests could be used to predict correctly the performance of rotary joints in the hard vacuum of space, then one could assume from the information given in Table 2-8 that there is no problem in the power-handling area. However, because the mechanisms of breakdown differ considerably under the two different environments, little correlation may exist. It is consequently impossible to state the general power-handling capability of rotary joints in space with any degree of confidence. As is usual in circumstances such as this, design data from ground applications is utilized for conceptual designs until simulated test or actual flight data becomes available.

2.8.2 MAJOR PROBLEMS

The major problem area relating to the utilization of RF rotary joints in broadcast satellite missions is the general lack of design data necessary to cope with the high-power breakdown problems that occur in hard vacuum. The information available from ground tests of rotary joints under controlled environments may be of limited value in predicting power handling in space. In ground-based systems, the breakdown phenomenon is usually associated with gas discharge where ionization of the gas molecules provides the conducting path required for arcing or voltage breakdown.

In the hard vacuum of space, the breakdown phenomenon is characterized as a multipactor breakdown. This breakdown is triggered primarily by secondary electron emission. For multipacting to occur, an electrical-mechanical resonance must exist between the magnitude of the RF field, the frequency, and the physical dimensions of the component under consideration. The multipactor effect can, however, persist over a considerable range of variation of these three parameters. More importantly, the multipactor effect may induce side effects that can trigger arcing which is similar to that observed in a gas discharge breakdown. These side effects may be those associated with localized heating and changes in the conductor work function, or with outgassing of the material itself and the resulting plasma.

There is also cause for concern in the rotary joint conductor temperature rise due to dissipative heating. Thermal design should be sufficiently effective so that temperature equilibrium would be reached by heat radiation before thermionic emission would ensue. However, the work function of the conductors in question would undoubtedly decrease and, therefore, make secondary emission more of a problem, even outside the multipactor region. It is important to realize that, although precautionary measures will be taken against multipacting, there is still a possibility that a high-altitude breakdown environment will be created due to all other complex side effects. The amount of experimental data available is inadequate and, therefore, a high degree of confidence in theoretical or conceptual designs does not exist.

Potential problem areas are identifiable and to some extent can be addressed during rotary joint design. The rotary joint dimensions should be chosen such that the resonance condition required for multipacting at a given power level and frequency will not occur. Outgassing from the rotary joint conductors, choke bearings or lubricants due to dissipative heating should be minimized. Material outgassing from the spacecraft itself should be minimized so that entry through an open feed radiator is curtailed. Allowable conductor temperature rise may be controlled in concept by heat radiation devices.

2.8.3 CURRENTLY FUNDED EFFORT

Current programs for a study of Antenna Pattern Shaping, Sensing and Steering (NAS 3-11524 and NAS 3-11525) include a study of RF rotary joint design for multi-channel space transmission at power levels of approximately 1 kW per channel.

2.8.4 ADDITIONAL EFFORT REQUIRED

Experimental work is required to establish performance criteria in terms of RF power for the UHF, S- and X-bands in order to predict power-handling capability.

A theoretical investigation of breakdown problems in a high vacuum should be conducted. Off-the-shelf RF rotary joints should then be tested under high-power conditions in a high vacuum for frequencies in the UHF, S- and X-bands. After these tests, the rotary joint designs should be modified as necessary to ensure high power-handling capability without breakdown in a high vacuum. Finally, the maximum power capability of the modified designs should be established.

2.9 PARABOLOIDAL ANTENNA

2.9.1 GENERAL CAPABILITY

The capability of paraboloidal reflector antennas for broadcast satellites is best evaluated by assessing the technology state of the art of:

- Paraboloidal reflectors
- Paraboloidal feed systems

The general state of the art of reflector type antennas with diameters less than 30 feet is being developed. For example, the Apollo and Lunar Excursion Module tracking and communications antennas (flown in 1969) possess parabolic reflectors with diameters of approximately 2.5 feet that are suitable for S- and X-band operation as far as surface tolerance is concerned. The ATS-F/G 30-foot reflector, designed with an rms surface tolerance of approximately 0.050 inch, gives a capability of operation from the UHF through the X-band frequency range for this relatively large, erectable antenna. The ATS reflector has already been successfully erected in ground test, and surface tolerance measurements and launch vibration tests have been performed.

The antenna feed system for use in a space environment has not been adequately developed with respect to feed interaction, control of side lobes, and high power operation. The antenna feed system is composed of the primary feed, transmission line, rotary or flexible joints and polarizers. Many problems can be anticipated in the feed system area for power levels over a kilowatt.

In addition to problems of the feed system, there are several areas relating to the paraboloid antenna performance capability where a requirement for high power broadcast operation introduces additional complexities and problems not generally encountered in low power systems. These additional problems affect the areas of beam pointing, beam shaping, and generation of multi-beam patterns.

2.9.2 MAJOR PROBLEMS

The major problem in the paraboloid antenna area is the general lack of knowledge necessary for the design of antenna feed systems (single and composite feeds) capable of high-power operation in the hard vacuum of space. The solution to the high-power handling problem will be achieved only when the breakdown problems caused by factors such as sublimation, condensation, multipacting, outgassing, plasma, photoelectric effect, and allowable conductor temperature rise are fully understood and controllable. At present, this is not the situation, therefore, design uncertainties still exist for high-power antenna feed systems build to operate in a space environment.

Additional problems relating to high power transmission using a paraboloid antenna were mentioned in the previous section. The first of these is beam pointing. For low-power systems, the technology available from ground-based systems is sufficient to cope with the design problems. For high power systems, where flexible transmission lines and/or rotary joints would have to be significantly larger in size to adequately handle the large amounts of power without breakdown and with adequate thermal dissipation, considerable interface complications with the gimballing system can be anticipated.

A second area of consideration relates to the changes required and difficulties introduced in the reflector and feed system if there is a requirement for high-power beam shaping. Elliptical beam shapes would utilize power more optimally for irregular shaped coverage areas. Shaped beam systems are widely used in many commercial ground applications, so that the design techniques are well established. However, without additional effort for development of high-power feed systems for space applications and some structural and packaging design investigations, it is questionable whether shaped-beam, high-power reflector antennas will be available by the mid-1970's.

A third area relates to multi-beam antennas. The power-handling problems for these antennas are multiplied by complex feed interaction. The increased side-lobe and coma-lobe levels resulting from multiple feeds and feed displacement from the focal point may be unacceptable.

Thermal dissipation from waveguide is a problem for high-power broadcast satellites. At X-band frequencies, the waveguide loss (e.g., for rectangular waveguide type WR90 at a frequency of 12.2 GHz) in an earth-based system is about 0.38 dB per 10 feet: at S-band (e.g., type WR340 at 2.5 GHz), the loss is only about 0.07 dB per 10 feet. However, these ratings are for a ground environment where convection, conduction, and radiation from the waveguide are all possible means of cooling, and where forced air cooling might even be employed. In a space environment, however, cooling of the waveguide must depend upon radiation only, or some combination of conduction and radiation. Thus, the magnitude of the losses stated above may not be correct for waveguide operation in a space application, and therefore further investigation is needed.

2.9.3 CURRENTLY FUNDED EFFORT

In the paraboloidal reflector antenna area, the 30-foot ATS-F/G reflector model development is currently being funded by NASA and internally by Goodyear Aerospace.

Under NASA Contracts NAS-W-1438, NAS 8-11818, and currently under NAS 8-21460, General Dynamics has performed an erectable antenna development study resulting in a deep truss antenna design for a rigid paraboloid up to 300 feet in diameter. Radio frequency tests have been performed on a 6-foot operating model of this design at 15 GHz.

Additional studies will be performed under NASA contracts NAS 3-11524 and NAS 3-11525.

Effort in the antenna feed system area for high-powered broadcast satellite systems is almost nonexistent. Companies and government organizations that have been involved in planetary or interplanetary satellite missions and have observed RF breakdown problems in hardware have devoted some research toward the general solution of these problems. These organizations are NASA, GE, Hughes, JPL, MIT and SRI. Multipacting has been one of the major sources of breakdown in these missions. Moreover, the power levels involved have been several orders of magnitude lower than what is anticipated for broadcast satellite missions. Thus, the probability of multipacting type of breakdown occurring in the latter application will be greatly increased.

The beam-shaping problem was assessed by Goodyear Aerospace when an inflatable wire-grid tube version of a reflector with an elliptical aperture was built. Effort along these lines appears to have diminished, and the present state of development of shaped-beam antennas for high-power broadcast satellites is rather low. Current programs for a study of Antenna Pattern Shaping, Sensing, and Steering (NASA NAS 3-11524 and 11525) have as their major objective the design study of a multibeam space antenna system with multi-channel capability. Included in the study will be the ability to re-orient the beams in space. Maximum power outputs of 1 kW per channel and of 4 kW for all channels combined are requirements.

2.9.4 ADDITIONAL EFFORT REQUIRED

Additional theoretical and experimental work is required to assess the performance and power-handling capability of single and multiple antenna feed systems under the conditions of hard vacuum. This effort should not be restricted to the testing of only a particular component of the feed system (e.g., a rotary joint), but should include individual testing of each component as well as subsystem testing of the entire integrated feed assembly. In the past, practically no effort has been applied to the design problems associated with primary feeds for kilowatt-level antennas in space. However, it is in the primary feed area where intense electromagnetic fields exist. In combination with phenomena such as solar radiation, outgassing and plasmas, these strong fields can result in high-power breakdown. Unlike the rotary joint or transmitter line, which are generally closed or shielded, the high-power primary feed is open and exposed to the hazards of space such as solar radiation and plasma which may form around or be intercepted by the satellite vehicle. Therefore, the primary feed may be the weakest link in the feed system chain, with respect to high-power breakdown, and an area requiring the majority of theoretical and experimental efforts. A theoretical investigation of potential high-power breakdown problems in the RF feed should be conducted for UHF, S- and X-bands.

It is important that the RF rotary joint, transmission line, and RF feed be investigated on an individual component basis so that design data on high power conditions is available for each component. It is also important that the entire feed system be tested and evaluated under high-power, high-vacuum conditions. As a result of the tests, design criteria for high-power feed system design should be established for all the pertinent frequency bands.

For the beam-pointing problem, the design limitation for prime-focus scan in high power paraboloid systems should be assessed and performance bounds should be established.

For multibeam antenna problems, the high power design criteria for single RF feed systems should be reviewed and evaluated to assess the potential multibeam transmission problems. High-power testing of primary feed clusters under high vacuum should be performed if results from prior single-feed tests indicate a possible problem area.

For beam-shaping problems, the previously developed high-power feed system design criteria should be assessed and then performance limitations for shaped beam primary feed designs established.

If reflector antennas present insurmountable problems at higher power levels, mechanically steerable arrays could be the next step because high-power can then be distributed over many elements. Redirective electronically-steerable phased arrays offer additional advantages in satellite beam steering and attitude control requirements for the future; however, these latter advantages are offset by cost, weight, and efficiency penalties.

2.10 MECHANICALLY STEERABLE ANTENNA ARRAY

2.10.1 GENERAL CAPABILITY

One example of a mechanically steerable array which has been flown is the S-band waveguide-slot, Surveyor antenna built by Hughes. This planar array antenna has an aperture 38 inches x 38 inches, a gain of 27 dB, and an aperture efficiency of 70 percent. The North American Rockwell Company is studying a mechanically steerable phased array utilizing endfire elements and sinuous waveguide feed lines.

The chief advantages of a mechanically steerable array over a paraboloid type antenna are the distribution of power over the entire radiating aperture and the use of (many) low power transmitter power amplifiers. The disadvantages of packaging and higher weight, however, are usually of such magnitude that paraboloids are preferred. The mechanically steerable array which would have application for broadcast satellite missions, that is, one with distributed amplifier output devices, is not now being investigated. On the other hand, various redirective phased array studies currently in progress should precipitate knowledge also useful for mechanically steerable designs.

In general, the state of the art for mechanically steerable arrays must be considered relatively low in so far as adaptability of any present designs to high power broadcast satellites is concerned.

2.10.2 MAJOR PROBLEMS

The problems existing in the implementation of mechanically steerable arrays are two-fold. The first problem area relates to the difficulty in mechanically packaging and deploying the array, regardless of the mechanism chosen to excite the array elements. The design of the antenna for packaging within the shroud and for subsequent erection in space is considerably more difficult than for a parabolic reflector antenna.

The second problem involves the method chosen to feed the array elements. Possible passive feed techniques are: a) to use a series-fed transmission line or waveguide, or b) to utilize corporate feed networks, such as the Butler matrix scheme. As an alternate scheme, each individual element or element group (i.e., subarray) may be associated with its own output device or amplifier.

The passive network feed technique is bulky, heavy, difficult to package and deploy, and considerably limited in bandwidth capability. Extending the bandwidth capability, and hence the number of channels, increases design problems by at least an order of magnitude. The passive network feed technique is, therefore, not as flexible in performance capability as is the mechanically steerable array with individually fed array elements.

However, the problems created in distributing RF signals from individual output devices to each element are not minor. The major problem area lies in the required phase stability for the output amplifiers in order to produce a tolerable rms phase error over the entire array aperture. This problem area has not been addressed until now primarily because a real need for a mechanically steerable array has not yet been established. If high-power primary feed system problems can be solved for a reflector type antenna within a reasonable time period, distributed amplifier array antenna problems may be studied not in connection with mechanically steered arrays but rather as part of the more advanced, redirective phased array antenna systems. Consequently, the mechanically steerable array should receive only a limited level of investigative effort unless something unexpected occurs in the reflector antenna design area which prohibits its general usage for high-power broadcast satellite missions, or reliability of high power transmitters is too low, forcing the use of multiple low power amplifiers.

2.10.3 CURRENTLY FUNDED EFFORT

The efforts of Hughes and North American Rockwell have been discussed in paragraph 2.10.1. Other companies, including General Electric, are pursuing various electronically-steerable phased array activities from which some results could be adapted to mechanically-steerable array requirements. For example, for the past 2 years redirective antenna arrays have been investigated by GE. During the course of these investigations, a 79-element, randomly spaced, S-band phased array antenna (Figure 2-5) was built. To assess the performance of the antenna, a 79-port, stripline power divider was built, and the antenna pattern characteristics and gain were measured. This antenna system, which possessed a gain in excess of 30 dB, is representative of the antenna and corporate feed structure required for a mechanically steerable array. Although the stripline power divider is not suitable as a high-power device, the applicability of results to the mechanically steerable array antenna design is evident.

2.10.4 ADDITIONAL EFFORT REQUIRED

Additional investigations may be required for the mechanically steerable array antenna depending upon the high-power capability available from reflector antenna systems. If major problems develop in the high-power feed system design for reflector type antennas, and if these problems severely limit the broadcast satellite effective radiated power, then the logical progression would seem to lead next to a mechanically steerable array system.

Any additional effort for advancing the state of the art of mechanically-steerable, high-power arrays should include both structural and electrical considerations. The deployment and erection techniques used for large arrays should be investigated and engineering models built to justify design approaches for these techniques. In addition, the behavior of the distributed amplifier output device in the mechanically-steerable system should be studied and a partial array built and evaluated in terms of high power and efficiency.

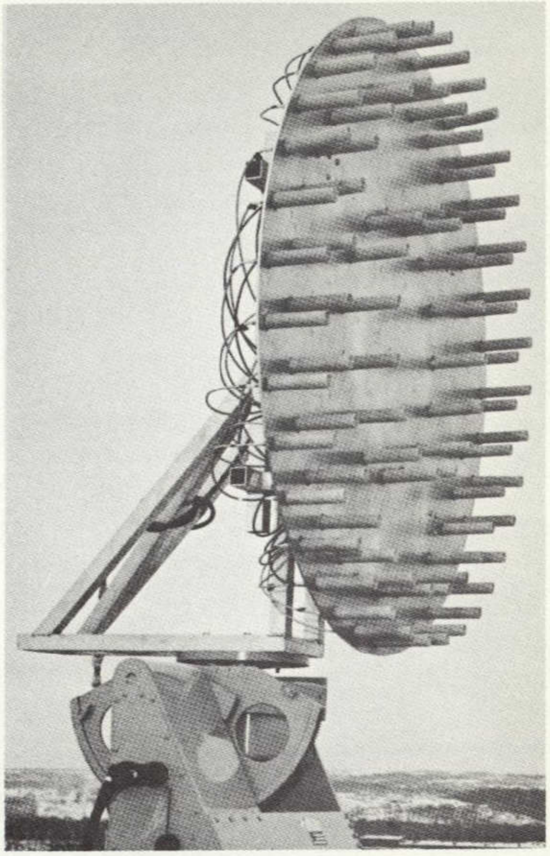

Figure 2-5. A 79-Helical Element Phased Array —Transmit Portion

2.11 ELECTRONICALLY STEERABLE PHASED ARRAY

2.11.1 GENERAL CAPABILITY

Only the redirective self-adaptive type of electronically steerable antenna array will be considered in this discussion. Other types of phased arrays, such as the commanded systems utilizing phase shifters or beam switching networks (having extensive ground application capabilities) are generally part of a radar system and are not readily adaptable to broadcast satellite applications.

As applied to space-borne systems, a redirective antenna system is a cooperative ground-to-satellite system using directive beams for receiving and/or transmitting, and having provisions for keeping the beams pointed in the proper direction. In this system, phased array antennas are employed in the satellite for receiving and transmitting functions.

An originating ground station transmits to the satellite the information to be relayed in combination with a pilot signal. By heterodyne action, the satellite antenna electronics processes the signal received by each array element so that all of the received signals are then in phase. A user ground station desiring to receive the information from the satellite emits a proper pilot signal. This is received at the satellite and heterodyned with the previously processed signal in such a way as to produce a conjugate phase in each array element. The transmitted satellite beam is thus automatically steered back in the direction of the user station.

The redirective type of phased array with its self-phasing, inherently inertialess, beam-pointing capability is in concept perfectly suited for broadcast satellite missions. While despun phased array antenna systems have been flown, no truly redirective antenna system has been launched. The Data Relay Satellite System (DRSS) presently being considered by the NASA Goddard Space Flight Center will probably constitute one of the first generations of satellites equipped with a redirective antenna system. Redirective antenna sizes up to 40 feet in diameter are being considered for the S-band range. The half-power beamwidth for this proposed DRSS antenna is approximately 1 to 2 degrees.

At the present time, the general capability of redirective phased array antennas systems for broadcast satellites must be classed as low and noncompetitive with reflector antennas.

Packaging and deployment of these antenna types is only in the conceptual stage. The weight of a redirective antenna system including amplifiers is estimated at the present time as approximately two to four times as large as a reflector antenna plus transmitter on a comparable basis.

The antenna system efficiency is presently low because of the limitations of the output amplifier devices and the way they are utilized in the system. A design of an X-band redirective antenna analyzed for ATS-F/G had a system efficiency of less than one percent. A General Electric design for an S-band redirective system that was developed during a 1967 company funded effort had an efficiency of a few percent.

Because of the increased complexity of these systems in both the number of radiating and amplifying elements plus the associated circuitry, (phase shifters, diode switches, power dividers, couplers, etc.) the cost of the redirective phased array antenna system is estimated at present to be 2 to 4 times the cost of a reflector antenna system with comparable performance. In addition to the increased cost of the antenna system itself, the presently available low efficiency would result in increased solar array costs for any system requiring substantial power levels.

It is, therefore, concluded that the present state of the art for redirective phased array antennas is inadequate for the majority of anticipated broadcast satellite missions, and the general capability is consequently classed as low.

2.11.2 MAJOR PROBLEMS

Certain problems exist at the present time in the implementation of the redirective phased array antenna for broadcast satellite missions. The mechanical packaging and deployment of this array is considerably more difficult than for the reflector antenna. Approaches at present are largely conceptual and, hence, unproven.

The antenna system efficiency is constrained by the available output device efficiency for the particular frequency band under consideration. This device efficiency is indicative of the component state of the art at any given time but, in general, is constantly increasing. However, the output device efficiency is sometimes deceiving. For example, a transistor amplifier at UHF may have an efficiency of 35 percent, but the gain of this device may be

only 5 to 6 dB. Thus, if a gain of 20 dB is required for the output device, a cascaded amplifier chain is required. In this case, the required drive power becomes a significant consideration and the over-all amplifier efficiency may decrease to 10 percent or less.

In addition to the behavior of the output device itself, the associated circuitry required to perform the heterodyning function (for the redirective capability) is complex and difficult to implement at a reasonable weight even when microminiaturization techniques are used.

2.11.3 CURRENTLY FUNDED EFFORT

In spite of the existing problems associated with the redirective phased array approach, the potential performance capability is so great that many companies have invested their own funds for the development of these systems. The most prominent among those firms who are participating in the development of these systems are the General Electric Company, AIL, Hughes, Sylvania, RCA, Texas Instruments and Lockheed.

The Orbiting Data Relay Network Study, recently performed by Lockheed and RCA, involved the conceptual design of S-band redirective antenna systems. The Data Relay Satellite System study by AIL, just getting under way for NASA Goddard SFC, involves similar requirements for a redirective phased array for S-band. For the Air Force MERA program (AF33(615)-1933), Texas Instruments has developed a laboratory prototype of an X-band, redirective, solid-state phased array antenna.

Figures 2-5, 2-6, and 2-7 are photographs of antennas and antenna elements which have been investigated by GE (under internal company funding) for various phased array antenna requirements. The planar array of endfire helical elements (Figures 2-5 and 2-6) was built to demonstrate the feasibility of randomly thinning a planar aperture, then recovering with the use of endfire elements the majority of gain lost by thinning. There are a total of 158 elements in this array, 79 transmit elements at 4 GHz and 79 receive elements at 6 GHz. The thinned transmitting portion (shown in Figure 2-5) was pattern-tested and the measured gain was in excess of 30 dB. The corresponding aperture efficiency was nearly 50 percent so that, in essence, much of the gain lost by thinning was recovered by the increased element gain.

A 7-element sub-array of cavity-backed spiral antennas is shown in Figure 2-7. The measured element gain of this sub-array ranged from 14 to 16 dB depending on the frequency and spiral spacing. Such a sub-array element is ideal where considerable element gains and yet a thin element profile are required.

2.11.4 ADDITIONAL EFFORT

The redirective phased array antenna approach is not likely to displace the paraboloid antenna in the first generation broadcast satellite regardless of the magnitude of funding which might be applied toward this goal. Many companies are gradually advancing the state of the art in this area, but the fundamental problems to be solved relating to output device efficiency and power output require time as well as money. In addition, the solutions to problems involving weight reduction through the use of fully integrated or hybrid circuitry should be

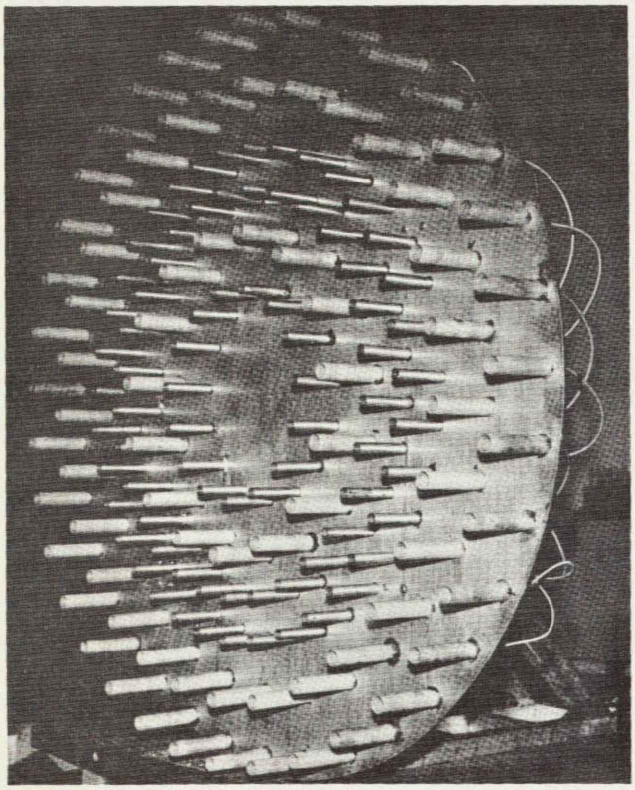

Figure 2-6. A 158-Helical Element Phased Array - Transmit and Receive

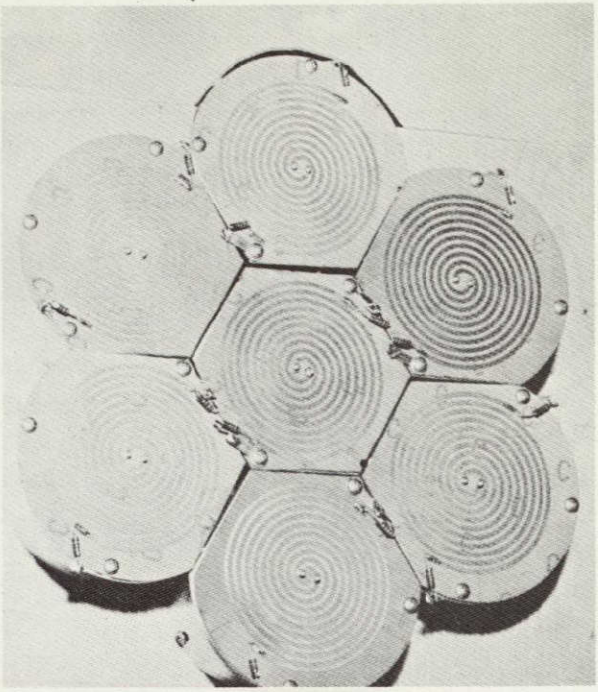

Figure 2-7. A 7-Element Sub-Array of Cavity-Backed Spiral Antennas

such that the performance is not compromised by the reduction in weight and size. Consequently, technology contracts in the redirective phased array antenna area would serve to expedite the eventual utilization of these systems for TV Broadcast Satellite missions.

Two main areas of additional effort are required, structural and electrical. Large antenna deployment and erection techniques need to be investigated and engineering models need to be built to justify the approaches. Efficiency limitations of the presently available output devices and the effect on antenna system efficiency should be established. Suitable redirective array circuitry, using current miniaturization techniques, should be designed. Partial arrays with the best state-of-the-art components should be built and the system performance then evaluated.

One major impact of the redirective electronically-steerable phased array upon satellite cost and weight is by way of its effect on the attitude control system requirements. By using such a phased array, it is possible that the attitude control subsystem accuracy requirement might be relaxed, for example, from ± 0.5 degree to ± 5 degrees. The electronically steerable array may improve the performance of the satellite system because of its inertialess beam-steering. Thus, with a phased array, there would be a minimum interaction between the antenna subsystem and the attitude control subsystem, and overall system performance could be enhanced.

2.12 FLEXIBLE BODY AND ATTITUDE CONTROL INTERACTION

2.12.1 GENERAL CAPABILITY

Mission requirements for larger, more complex spacecraft (which are representative of medium and high power broadcast satellites) have already introduced many new structural concepts and unusual vehicle configurations. Inflatable and erectable structures are being developed. All of these large flexible structures have little of their total mass allotted for structural stiffness which is not required in the relatively mild space environment.

The complete analytical description of space vehicle motion involves the highly nonlinear coupling of rigid body motions with flexible spacecraft deflections. The motion of any vehicle in flight is best described by nonlinear equations; however, the linear approximations to these equations have been adequate for design purposes in the past. Linear approximations are valid as long as: a) the structure behaves in a linear manner, and b) the Euler cross-coupling terms are negligible. However, for very large, very flexible spacecraft, these nonlinear (i.e., Euler cross-coupling) terms are not negligible and, in fact, sometimes predominate over the first-order terms. Flexible appendages, such as long rods and hinged members which are usually erected in space, generally exhibit low natural frequencies which may lie within the attitude control filter bandwidth, resulting in command errors to the controller. Therefore, in any dynamic analysis of flexible spacecraft, the interaction of the structure and the attitude control system is of paramount importance in both the structural and control system designs.

The fact that the equations of motion cannot always be linearized and that the control-structural interaction problem becomes very important precludes exclusive use of the highly-developed frequency domain solutions used so successfully in the past in control design and in the solution of control-structural interaction problems. The application of time domain solutions appears to be the only feasible alternative at the present time. It has been the primary goal of both the current in-house projects at GE and the GE contract with NASA MSFC (NAS 8-21043) on flexible vehicle dynamics to obtain solutions in the time domain. A secondary purpose is to establish criteria for determining where frequency domain solutions can be employed advantageously.

The nature of this broad-based attack on the dynamics of spacecraft dictates that it cannot be done from the parochial view of only a control dynamicist, structural dynamicist, or trajectory analyst; but it must be performed at the systems level where every discipline must contribute and interact to solve the engineering problems associated with the total space vehicle system.

Work at General Electric, over a period of about three years, has led to the formulation of equations of motion of a collection of bodies related to a rotating space frame, coupled through structural constraints, and capable of being forced or monitored at any coordinate.

Computing systems to perform the evaluation of system performance have been developed for use on the IBM 7094 and have been used in analysis of control system/structure studies on the ATS-4, a flight experiment study for NASA MSFC, some cable studies, and an analysis performed for ATS-2.

Programming of computing capability suitable for the UNIVAC is presently under way under contract to NASA MSFC (addendum to contract NAS 8-21043).

2.12.2 MAJOR PROBLEMS

The major problem is the application of the available analytical tools to a total spacecraft design, such as a broadcast satellite system, and then the verification of the analysis with a test program.

Although both the analytical and computational tools are available, experience in application to given mission requirements is lacking; therefore, the procedures cannot be considered operational. To achieve this status requires application to specific real problems and verification by test.

2.12.3 CURRENTLY FUNDED EFFORT

The General Electric Company is currently funding programs to evaluate the effects of flexibility on spin-stabilized motion, and the parametric evaluation of the cross-product coupling effects of vehicle parameters.

A programming effort to develop a system, comparable or superior to the IBM 7049 system in use at GE, for computation of the motion response using UNIVAC is in progress under contract to NASA MSFC.

Most aerospace companies are expending some level of effort on the problem of flexible structure/attitude control interaction. However, the above programming effort represents the only known contractual effort on the general analysis of the problem.

2.12.4 ADDITIONAL EFFORT REQUIRED

Most of the effort to date has been directed to the manipulation of structural analysis into a form in which it is compatible with control system analysis so that the flexible motion of the coordinates can be monitored. Figure 2-8 illustrates the nature of the problem. The purpose of a control system is to maintain the orientation of the vehicle constant with respect to inertial space or some other reference frame. This is ordinarily accomplished by sensing the position of the body axis with attitude sensors at point "a" and by firing thrusters at points "b" and "c." The magnitude of the thrust at each point is T. Due to deformation of the connecting member (shown between the larger and smaller bodies) when the thrusters are energized, the attitude sensor indicates a pointing error of ϵ even though the body axis has a true pointing error of β. This would result in an incorrect error signal being fed back to the control system unless the sensor coordinate relative to the body axis were to be monitored and used to correct the error feedback signal.

A form of analysis which allows evaluation and selection of overall spacecraft candidate configurations on the basis of controllability and flexibility has been developed. This is in addition to tools for detailed performance analysis.

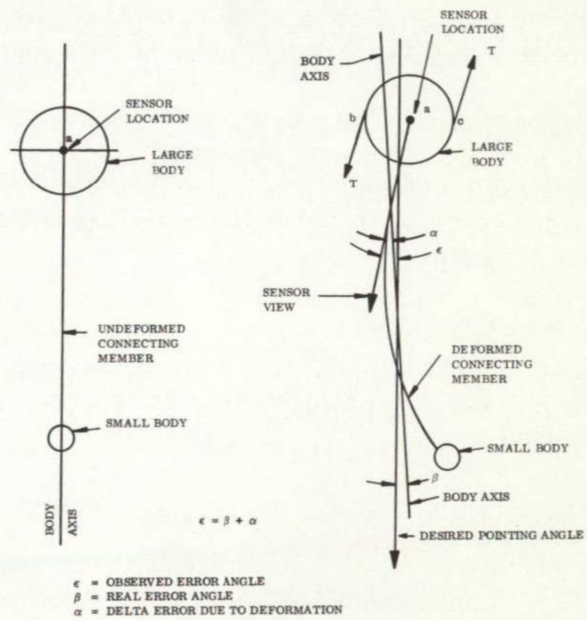

Figure 2-8. Effects of Flexible Body Motion on Pointing Error Signals

Various analytical and computational tools for detailed performance analysis are available. To achieve an engineering design capability, an effort is needed primarily to select and evaluate specific useful applications and then to exercise the system and bring the tools to an operational status. Flexible structure modes of vibration must be studied and the structure must be defined to adequately assess problems arising in solar array deployment, articulation and manufacture, antenna beam shaping, beam pointing, deployment and erection, and in attitude control and station keeping. Interactions of large flexible structure with its space environment and with an active attitude control system should be further investigated to avoid degradation of control accuracy and functional performance. A small number of configurations representative of deformation mode shapes should be analyzed over suitable ranges of sizes and frequencies in order to facilitate the selection of flight vehicle configurations, evolve design criteria, and evaluate the feasibility of actual final designs.

The steps to be taken as an initial effort should be the selection of a vehicle configuration for a typical broadcast satellite mission. Station-keeping requirements (representative of the largest disturbance) should then be defined. A structural synthesis, which would permit parametric variations, should be performed for the broadcast satellite chosen. From an evaluation of the parametric variations, the location, the size and the on-time of the thruster engine should be determined. The open loop responses of the vehicle due to the propulsion jets or other internal (e.g., articulation of an array) or external (e.g., solar pressure, meteorite impact) excitations should also be examined. Tradeoff criteria should be developed for acceptable antenna beam shape and beam pointing using closed-loop attitude control analysis. Finally, through parametric variations of attitude control and structure, fixes for obtaining satisfactory performance should be specified.

The scope of a follow-on verification test program and whether a ground or space experiment is warranted will depend upon the complexity and flexibility of the system configuration selected and the success of the analytical program.

2.13 THERMAL CONTROL

2.13.1 GENERAL CAPABILITY

The thermal control systems considered for cooling high-power transmitter tubes are heat pipes and active fluid loops. Heat pipes have been selected as the better approach due to their inherently higher reliability and operation without electrical power.

Heat pipes have been flight proven thus far on two occasions. An experiment of short duration was orbited on the Agena booster used for the ATS/A launch. This heat pipe was made from stainless steel and used water as a working fluid. Two heat pipes have been operating aboard the GEOS/B satellite for several months with no apparent degradation. They are made of aluminum and use freon for the working fluid. Two more heat pipes are to be used to cool a traveling wave tube (TWT) aboard the 1969 Mariner launch.

Ground-operated heat pipes have been used over a broad range of temperatures and power levels. One heat pipe test in conjunction with a heater simulating a GE L-64SA triode has demonstrated cooling to 500^{o}C at dissipated power levels in excess of 2.5 kW.

In another test, a heat pipe radiator has been employed to cool first a simulated traveling wave tube to 280^{o}C at a dissipated power level of 1.5 kW, and then the TWT itself to below 200^{o}C with 960 watts dissipated. Both systems were built and tested at General Electric.

A simplified schematic diagram illustrating the basic principle of operation of a heat pipe is shown in Figure 2-9.

2.13.2 MAJOR PROBLEMS

The major problems identified in the design of a heat-pipe thermal control system for broadcast satellites involve a lack of specific information on evaporator capability and the potential problems associated with the electrical and mechanical interfaces between the heat pipe and the heat dissipating elements of klystrons, traveling wave tubes, crossed field amplifiers, and gridded tubes. If the devices to be cooled have extremely high heat fluxes, more detailed data will be required concerning evaporator capacity and design. This data is currently available only for pool boiling and a few specific wicking configurations. More information is also required to identify possible problem areas at the electro-mechanical interface between the heat pipe and the device or tube to be cooled. These problem areas may include the effect of launch load environment on the heat

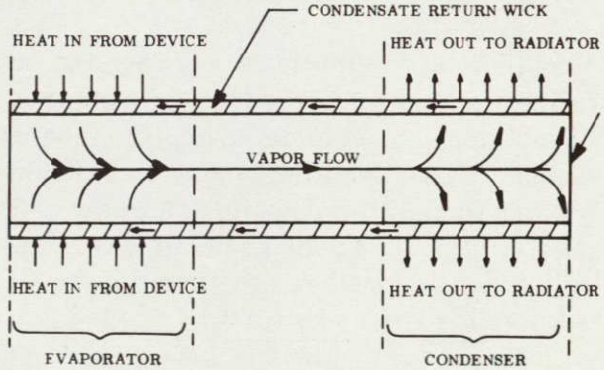

Figure 2-9. Heat Pipe Operation Schematic

pipe/device interface, and the possible problem of electrical isolation. Two plausible approaches to the latter problem are the use of insulating heat pipes, and the use of ceramic insulators inside or outside the device. Another possible approach (which may not always be achievable because of tube design limitations) is to operate the high thermal-dissipating tube elements at voltages close to ground potential wherever possible.

2.13.3 CURRENTLY FUNDED EFFORT

The major funded efforts in the area of thermal design for microwave tubes are being performed as parts of several microwave tube development contracts funded by NASA (NAS 1-7497, Varian; NAS 3-9719, Hughes; NAS 3-11513, Litton; NAS 3-11514, GE; NAS 3-11515, Litton; NAS 3-11516, SFD; and NAS 13-565, GE). Most of these contracts are primarily output-device design studies, but all have taken thermal control into consideration and all have used heat pipes as the primary means of heat transport. The NASA, ERC contract (NAS 12-565) has resulted in the successful cooling of a TWT by means of a heat-pipe radiator and the investigation of cooling techniques for other tubes. The final reports of all of these studies are due to be published early in 1969.

2.13.4 ADDITIONAL EFFORT REQUIRED

Future work in the area of heat-pipe design should be directed toward optimization of the evaporator. Present designs have evaporators capable of up to 300 W/in.^{2}. Above this power density (at a level referred to as the critical or burn-out heat flux), the wick dries out, and heat transfer through the heat pipe drops abruptly, causing a sudden drastic rise in evaporator temperature. In a tube where the power density is well below 300 W/in.^{2}, there is no problem. In many devices, however, power density can be several times this maximum, requiring thermal conduction paths to spread out the dissipated heat to an acceptable density. Since it is proportional to the power density, the temperature drop through these conduction paths is high, resulting in a reduced radiator temperature which requires more radiator area and weight.

By developing an evaporator with a burn-out heat flux considerably above presently used levels, the heat pipe can be brought much nearer the heat source, thus increasing the temperature at which the radiator can be allowed to operate. The higher the operating temperature of the radiator, the more effective its cooling ability.

Problems at the interface between the output device and the thermal control system are encountered due to several design requirements. Mechanical alignment may require flexible connections to avoid damaging the tube during either installation, launch vibration or thermal expansion. In addition, electrical isolation of high potentials is required by some high-power transmitter devices. A ceramic material, such as beryllia, has a high thermal conductivity (of the order of aluminum) as well as good electrical insulation properties.

2.14 GROUND RECEIVING SYSTEMS

2.14.1 GENERAL CAPABILITY

The TV ground installation considered for the broadcast satellite's missions consists of equipment which must be added to the conventional TV receiver to permit it to receive a signal from a broadcast satellite. This installation will normally consist of an antenna and a converter (frequency or modulation or both). The ground installations constitute a critical technology area because future improvements could permit:

1. Reduction in required satellite transmitted (and hence prime) power by:

   a. Use of wideband (e.g., FM) modulation techniques.

   b. Operation at frequencies where low ambient noise is attainable.

   c. Use of relatively large ground antenna apertures.

2. Improved spectral availability by permitting operation in spectral regions where more frequency bandwidth is available.

3. Low total system implementation costs where the ground equipments can be fabricated and installed at very low costs.

Both antennas and converters exist or can readily be designed which will easily meet all broadcast satellite performance requirements. However, these are high quality commercial and military equipments which cost much more than can be considered for home installations. In addition, low-cost commercial UHF TV antennas with gains of up to 20 dB can be bought quite cheaply; however, these are linearly (rather than circularly) polarized, and there are no low-cost antennas available at the higher (S-band and X-band) frequencies.

By 1971, it is anticipated that advances in the state of the art in components and circuits will have made the production of low-cost converters and antennas somewhat less difficult. However, studies aimed specifically at the broadcast satellite requirements are required to attain this anticipated state of the art since the electronics industry presently has no strong motivation to design such equipment.

2.14.2 MAJOR PROBLEMS

TV signal converters are devices which convert a satellite signal from some different frequency and/or modulation to an AM vestigial sideband signal frequency suitable for a conventional TV receiver.

The major problem in TV converter technology is economic, i.e., the question of whether a converter can be built at an acceptable cost. The converter cost is an important consideration in most broadcast satellite services. However, for those services where the audience size is extremely large, the total cost of adding converters may be so high as to become the predominant economic factor in the system. No such converters have been built because of lack of demand, and for the same reason the problem has been given relatively little attention by the industry. The cost of the ground antenna also promises to be quite important where large audiences are involved.

2.14.3 CURRENTLY FUNDED EFFORT

An investigation of the ground converter has been initiated by NASA, LeRC under Contract NAS 3-11520 to GE. This is a study in two phases, with the purpose of determining the feasibility and cost of representative TV converters. The first phase will investigate all appropriate techniques, screen them to obtain the most promising, with respect to performance

and cost, and provide designs and cost estimates for representative converters. During the second phase the selected types of converters will be designed, fabricated, demonstrated and delivered. Specific converters, illustrative of the configurations most likely to be preferred, were selected by NASA for this investigation. These are:

1. 2.25 GHz - AM

2. 2.25 GHz - FM, modulation index of 2

3. 12.00 GHz - FM, modulation index of 3

An antenna investigation was conducted at GE (as part of this broadcast satellite study) which involved designing and building a 10 foot paraboloid (Figure 2-10) with a gain of approximately 24 dB at 860 MHz, and preparing estimates of the cost of such an antenna if manufactored in quantity. This study indicated factory costs of the order of $50 per antenna in quantities of 5,000. So far as is known, this is the only investigation of the ground antenna problem which has been conducted to date.

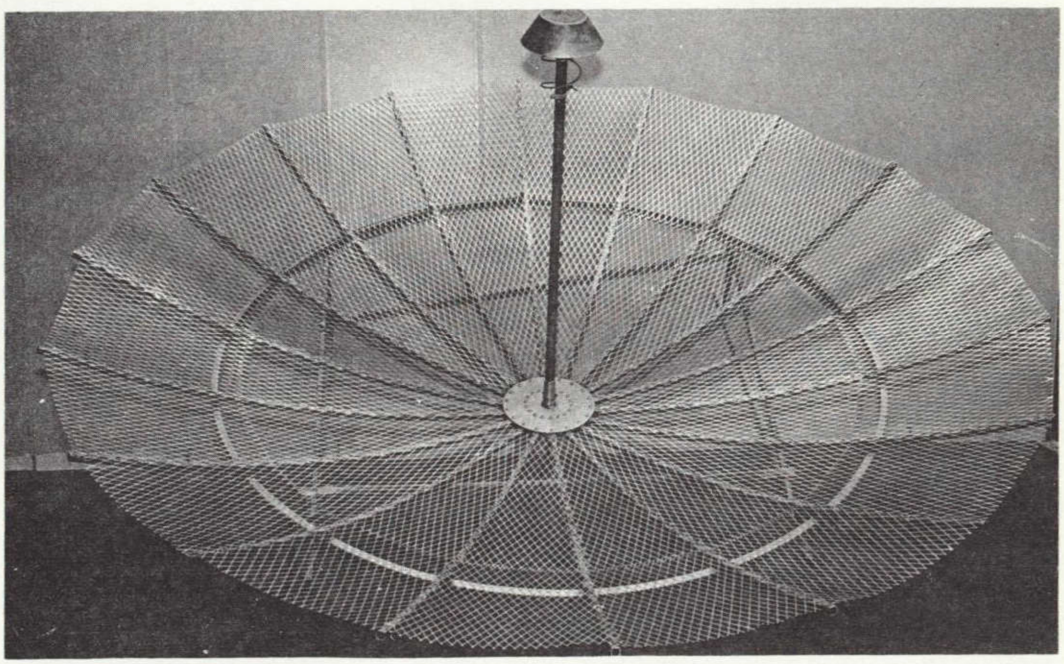

Figure 2-10. Ten-Foot Paraboloid Antenna for Ground Reception of UHF Television from a Broadcast Satellite or the ATS-G Satellite

2.14.4 ADDITIONAL EFFORT REQUIRED

The present converter program (NAS 3-11520) is an appropriate response to the needs of the converter technology area. However, certain additional efforts are desirable. These are:

1. Investigation of low cost threshold reduction techniques

2. Consideration of ultra-high frequencies in the 700 to 900 MHz range

3. Cost sensitivity to antenna performance improvements

It is recommended that consideration be given to a study of low cost antenna design across the 1 to 12 GHz frequency range and for gains of 20 to 35 dB. This study should include examination of alternate design approaches in terms of performance and cost parameters, design and test of developmental prototype antennas across the range of frequency and gain, and examination of the compatibility of the antenna with the ground converter.

Some consideration should also be given to the question of the convenience of high-gain antennas for home installation. A 25-dB paraboloidal antenna at 1 GHz, for example, is almost 10 feet in diameter, a size which might be unacceptable to the homeowner for a home installation in an urban or suburban area. Alternate approaches to the problem of obtaining equivalent apertures with physically smaller antenna configurations should, therefore, be considered.

If the need for very narrow receiving beamwidths becomes established for certain broadcast satellite services, electronically self-steerable array antennas may offer a more economical solution than mechanically steerable arrays and, therefore, warrant additional R&D effort.

SECTION 3

SUBSYSTEM TECHNOLOGY PRIORITY LISTING

One of the objectives of the broadcast satellite technology evaluation was to examine the candidate technology development programs previously described and to recommend some order of priority for additional effort required. The purpose of this section is to describe the criteria and the rationale used to rank the technologies discussed in Section 2 and to present the results of this evaluation.

3.1 RANKING CRITERIA EMPLOYED

The primary criteria used to rank the technologies were the estimated impacts that the particular candidate technology would have upon each of the following factors:

1. System cost
2. System weight
3. System performance and long life reliability (system feasibility)
4. Subsystem feasibility
5. Development risk
6. Lead time

It should be noted that not all six criteria were applicable to all candidate technology programs.

Cost may be analyzed in two basic ways: first, the impact on system cost using sensitivity models, and second, the cost of the development program. Obviously, a technology for which the system cost impact is a maximum and development cost is a minimum is a high priority candidate.

Feasibility can be interpreted in two basic ways, technical and economic. Although a fundamental requirement of any TVBS system is that it be at least economically competitive with its equivalent TV terrestrial system, technical feasibility was considered more significant than economic feasibility for ranking purposes.

Development risk refers to the estimated probability of successfully achieving the improvements identified for a technology once an adequate development program is begun.

Lead time is an important criterion particularly for those technologies, such as high power space transmitter tubes, where long development cycles have been historically required.

The lines of demarcation between each of these six criteria are not always clear-cut. These are many interdependent aspects involved in the application of these criteria. For example, system weight, performance, and long life can, in a sense, each be considered to have a system cost impact. Reduction in the weight of any subsystem could result in a cost saving (e.g., smaller booster requirement). Alternatively, this weight might be diverted into the addition of improved performance features. A performance improvement, on the other hand, might conceivably result in a cost saving, or might bring about greater accuracy, better ground reception, or greater variety or flexibility of operation without effecting any cost saving. Long system life reflects itself in a cost saving because fewer broadcast satellites would have to be launched within any given number of years in order to maintain continuity of TV service.

It should also be noted that system weight and volume considerations often dictate whether a technology presents a feasibility, cost, performance, or long life reliability problem. For example, if weight and volume were not constraints, one could build a solar array deployment mechanism for large arrays by making the structural elements of the mechanism very rigid, thick and strong and, coincidentally, very heavy. The realistic limitations imposed upon the spacecraft weight by available boosters, however, force the designer to seek a lighter weight solution, the feasibility of which may still be uncertain. Thus, additional effort should be applied to such a technology in order to establish its feasibility.

Development risk and lead time may also be interdependent criteria. Occasionally, a decision that a particular R&D effort involves a significant development risk is a function of the date on which the improved technology is needed. If a short development cycle is necessary, the attendant risk may be high; conversely, if there is sufficient lead time before the technology state of the art needs to be improved, then the development risk may be relatively small.

3.2 PRIMARY MEASURES IN CRITERIA APPLICATION

In applying each ranking criterion, some measures must be employed to assess the magnitude of the effect for each candidate technology. Among these measures are:

1. Qualitative engineering judgment

2. Calendar time or schedule

3. Subsystem sensitivity models for cost and weight

4. Vehicle weight or power

The use of subjective engineering judgement in applying the various ranking criteria is necessitated by the fact that only estimates and predictions of future potential impact upon the system are available for the ranking procedure. Calendar time refers to the time period (e.g., early 1970's, mid-1970's, etc.) when the different types and sizes of broadcast satellite vehicles are estimated to be ready for launch. Thus, the criticalness of each technology was assessed in terms of when it might be needed for a broadcast satellite mission. In connection with this measure, three selected power ranges (low, medium, and high) were established (see Table 3-1) to be representative of the range of broadcast satellites in the next decade. Each critical technology was evaluated at each of these three power levels. It should be noted that, in some cases, although a technology might be considered critical for use in a high-power broadcast satellite application, it might not be a critical item for the low-power satellite, and vice versa.

The results of the subsystem sensitivity computer models developed during the study are presented in Figures 3-1 through 3-4 which illustrate the percentages of total system weight and total fabrication cost attributable to each major subsystem. These percentages are plotted as functions of total system weights or costs as applicable. The subsystems with the most significant effects are identified in Table 3-2.

Table 3-1. Satellite Categories for Technology Ranking

Broadcast Satellite Solar Array Power Range (kW)		Approximate Satellite Weight Range (lb)	Estimated Satellite Fabrication Cost Range ($ M)	Estimated Launch Date
Low Power	1 to 3	600 to 1000	2.7 to 5.5	Early 1970's
Medium Power	3 to 10	1000 to 2500	5.5 to 13.6	Mid-1970's
High Power	10 to 30	2500 to 6000	13.6 to 32.0	Late 1970's

Table 3-2. Major Subsystem Impact (From Subsystem Sensitivity Models)

Satellite Solar Array Power	System Weight Impact	System Fabrication Cost Impact
Low Power (1 to 3 kW)	Power S/S Structure Large Antenna (>15 feet) Attitude Control Transmitter	Power S/S Attitude Control Transmitter
Medium Power (3 to 10 kW)	Power S/S Structure Large Antenna (>15 feet) Transmitter Thermal	Power S/S Transmitter
High Power (10 to 30 kW)	Power S/S Structure Thermal Transmitter	Power S/S Transmitter

Table 3-3 indicates criteria applicable to each technology for the three assumed solar array power ranges. In this table, an asterisk (*) in any column indicates that no major problems are anticipated for this system category. Any N/A entry in a column signifies that the technology is not likely to be used for that generation of satellites.

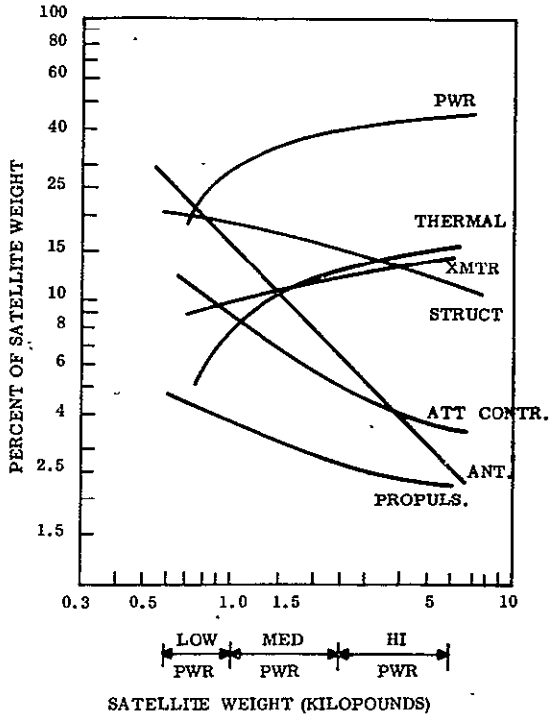

Figure 3-1. TVBS Subsystem Weight Sensitivity at UHF (0.8 GHz)

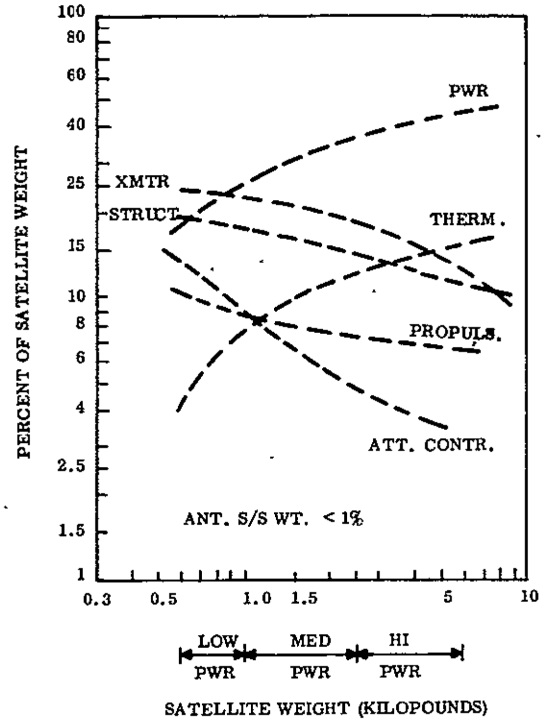

Figure 3-2. TVBS Subsystem Weight Sensitivity at X-Band (12.2 GHz)

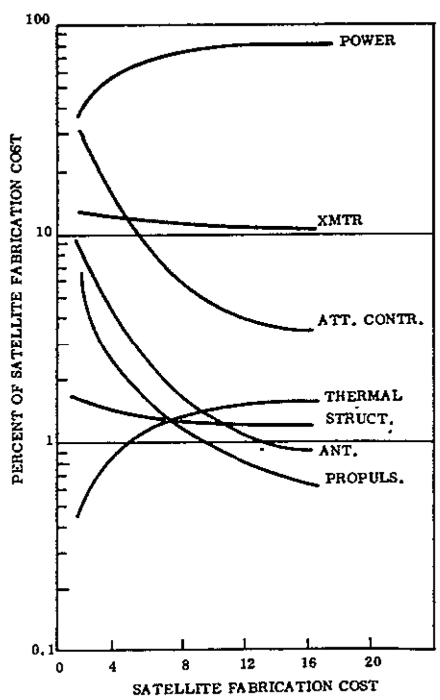

Figure 3-3. TVBS Subsystem Fabrication Cost Sensitivity for UHF (0.8 GHz)

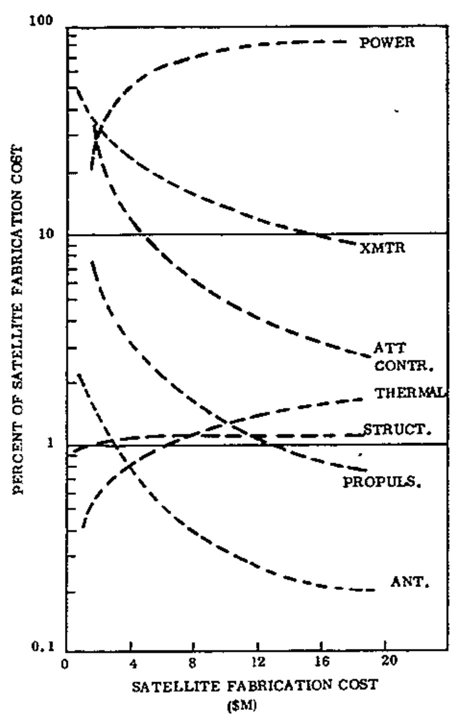

Figure 3-4. TVBS Subsystem Fabrication Cost Sensitivity for X-Band (12.2 GHz)

Table 3-3. Ranking Criteria Applicability
(not in priority order)

Sub-System	Critical Technology (Approximate Launch Date / Solar Array Power)	Broadcast Satellite System Categories: Early 1970's, 1 to 3 kW	Mid-1970's, 3 to 10 kW	Late 1970's, 10 to 30 kW
	Solar array deployment	*	*	C
Power	2-axis solar array drive	*	D	D
Power	Solar cell and array manufacture	N/A	N/A	A, D
Power	High voltage solar array	C, D	C, D	C, D, E
Power	High power dc rotary joint	C, D	C, D	C, D, E
Power	High voltage power conditioning	B, C, D	A, B, C, D	A, B, C, D, E
Power	High voltage handling	C, D	C, D	C, D, E
Transmitter	High efficiency gridded tubes	A, B, D	A, B, D	A, B, D
Transmitter	UHF transmitter circuits	A, B, D	A, B, D	A, B, D
Transmitter	High efficiency microwave tubes	A, B, D, F	A, B, D	A, B, D
Transmitter	Microwave tube transmitter circuits	A, B, D	A, B, D	A, B, D
Transmitter	High power RF components	B, D	B, D	B, D
	High power RF rotary joint	D	C, D	C, D, E
Antenna	Reflector antenna power handling	C, D	C, D	C, D, E
Antenna	Reflector antenna beam pointing	C, D	C, D	C, D
Antenna	Reflector multi-beam antenna	B, D	B, C, D	C, D, E
Antenna	Mechanically steerable antenna array	N/A	B, C, D	C, D
Antenna	Electronically steerable antenna array	N/A	N/A	C, D, E
Struct	Attitude control of flexible structures	N/A	A, B, F	A, B, C, D, E
Thermal	Heat pipes	D	D	A, D
Thermal	Thermal control interfaces with transmitter tubes	C, D	C, D	C, D
Ground Rec.	Ground receiving systems	A, B	A, B	A, B

Legend

A - System cost
B - System weight
C - Subsystem feasibility
D - System performance and long life reliability
E - Development risk
F - Lead time
N/A - Technology not applicable
* - Not a technology program

3.3 PRIORITY LISTING

Table 3-4 is a listing of the critical broadcast satellite technologies in descending order of priority. The final order was arrived at by a combination of assessing the state of the art, applying the six ranking criteria, employing best engineering judgement, and evaluating the overall criticalness of each technology to the broadcast satellite program over the next decade. Differences in priority among the items in any one category are considered to be relatively small, whereas major priority differences exist between the first, second, and third priority categories for each generation satellite.

It should be noted that the 22 technologies on the list were selected as the most critical ones from a larger potential candidate list during the course of the broadcast satellite study. Thus, all the items shown in Table 3-4 should be considered technologies to which additional R&D effort should be applied.

Table 3-4. TVBS Subsystem Technology Priority List

Satellite Class / Priority Category	Low Solar Array Power (1-3 kW; early 1970's)	Medium Solar Array Power (3-10 kW; mid 1970's)	High Solar Array Power (10-30 kW; late 1970's)
First	High Efficiency Microwave Tube Ground Receiving Systems High Voltage Power Conditioning High Efficiency Gridded Tube UHF Transmitter Circuits	High Efficiency Microwave Tube Ground Receiving Systems High Voltage Power Conditioning Attitude Control of Flexible Structures Solar Array Deployment High Efficiency Gridded Tube UHF Transmitter Circuits	Attitude Control of Flexible Structures High Efficiency Microwave Tube Ground Receiving Systems High Voltage Power Conditioning Solar Array Deployment High Efficiency Gridded Tube UHF Transmitter Circuits High Voltage Handling High Voltage Solar Array Thermal-Transmitter Interface
Second	Solar Array Deployment High Voltage Handling Thermal-Transmitter Interface Heat Pipes DC Rotary Joint RF Rotary Joint	High Voltage Handling Thermal-Transmitter Interface Heat Pipes DC Rotary Joint RF Rotary Joint High Voltage Solar Array High Power RF Components 2-Axis Solar Array Drive	Heat Pipes DC Rotary Joint RF Rotary Joint High Power RF Components 2-Axis Solar Array Drive Solar Cell and Array Manufacture Reflector Antenna Power Handling Reflector Antenna Beam Pointing Reflector Antenna Multi-Beams Microwave Transmitter Circuits
Third	High Voltage Solar Array High Power RF Components Reflector Antenna Power Handling Reflector Antenna Beam Pointing Reflector Antenna Multi-Beams Microwave Transmitter Circuits	Reflector Antenna Power Handling Reflector Antenna Beam Pointing Reflector Antenna Multi-Beams Microwave Transmitter Circuits Mechanically Steerable Antenna Array	Mechanically Steerable Antenna Array Electronically Steerable Antenna Array

GENERAL ELECTRIC

SPACE DIVISION

SPACE SYSTEMS ORGANIZATION